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Table of contents

Monitoring

How can smart data analytics improve the way of information provision? -The trend of methods and an exploratory analysis-

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Abstract

Electricity companies are starting to install smart meters in the residential sector; however, data analysis methods for smart meters are not sufficiently developed and no overview has been published. Therefore, we have surveyed data analysis methods for smart meters and identified various problems. Data objectives can be categorized into seven types, including ‘support for efficient energy use’ to increase the efficiency of energy-saving and demand-response programs, and ‘support for tariff selection’ to allow comparison of electricity bills. Data analysis methods supporting these objectives can be categorized into five types, including ‘simplified disaggregation’ to estimate what kinds of activities cause demand based on the master switch load curve, and ‘life pattern estimation’ based on occupancy rate. To test these data analysis methods, exploratory analysis was conducted to estimate temperature-sensitive demand and life patterns for individual households. In our exploratory analysis, regression analysis incorporating life pattern estimation extracted the temperature-sensitive demand from the master switch load curves of four households. In addition, the life pattern estimation identified the demand-active level of each household in a specific hour or day. The information we obtained can be used for targeted advice or demand response programs to reduce the demand of heavy consumers who are at home in the afternoon. Future smart meter data use is also discussed.

Introduction

Electricity companies are installing smart meters in the residential sector. Objectives of smart meter data use are being investigated; for example, the wide variety of feedback about residential electricity consumption. There are various data analysis methods that are used for these objectives. In recent years, examples of analysis based on data compatible with smart meters in Japan have been published, corresponding to the acceleration of smart meter installation and the increase in actual data available for research. Examinations of these data analysis methods are scattered across various articles and are not well organized. Thus, it is difficult to get an overview of smart meter use, although there are review articles on specific analysis methods. Therefore, it is necessary to survey data analysis methods for smart meters and to identify the relevant problems [1]. Here, we summarize the survey results and conduct exploratory analysis of estimating hourly temperature-sensitive demand and other properties for individual households. Furthermore, we discuss the future issues for smart meter data use.

Trends in Methods

Data Objectives

In this section, we describe the seven objectives of smart meter data use shown in Table 1.

Support for Efficient Energy Use

Increasing the quality of feedback or energy conservation tips based on 30-min data can help promote energy conservation behavior or recommend new electrical appliances with energy-saving products. The feedback system that allows customers to browse smart meter data on the web or dedicated terminals is effective for customers who actively search for information. However, this method is not appealing to passive customers because energy is not a main everyday concern. These customers access the feedback systems less and less, until they rarely access it [2].

Therefore, strategic feedback or provision of energy conservation tips and replacement of old appliances with energy-saving appliances based on each customer's energy consumption is required. For example, optimizing graph representation and writing style by applying insights from behavioral science, and presenting targeted tips on heating equipment or heat insulation for consumers who use large amounts of energy in winter would appeal the passive customers [3].

Support for Tariff Selection

Different customers are interested in different tariff menus, depending on whether they consume large amounts of energy during the day or night, or on weekdays or holidays. Suggesting tariff menus suited to each customer's life style based on smart meter data could improve customer satisfaction. After the full retail liberalization of the electricity market scheduled in 2016 in Japan, this support will be more important. Additionally, several trials to reduce peak time demand using demand response (DR) programs are being investigated.

Efficiency Improvement of Management of End-User Appliances

Incorporating smart meter data with energy management systems, including home energy management systems (HEMS), could allow more efficient control of end-user equipment, such as domestic electrical appliances, based on each consumer's consumption or electricity generated by photovoltaic (PV) systems. For example, temperature settings of air conditioners could be changed, or the discharge and charge of rechargeable batteries and electric vehicles (EVs) could be optimized.

Supply of New Services

Smart meter data can also be used for new services that support everyday life; for example, monitoring elderly people, security, healthcare, and for marketing other products or other services.

Improvement of Targeting Strategies

The number of customers who respond and how the customer responds to the services could vary. It is necessary for electricity companies to target suitable customers or to customize the content of the intervention to make it more cost-effective. For example, targeting customers who tend to be at home and consume a large amount of energy running air conditioners during peak demand time could increase the efficiency of DR programs [4]. Furthermore, there are several examples of using smart meter data for designing tariff menu suggestions [5].

Improving Management of Electricity Distribution Equipment

Electricity distribution systems are affected by customer's electricity consumption patterns, PV systems, and the future prevalence of EVs. Accumulating smart meter data to investigate the actual status of electricity load can aid the rationalization of asset management of electricity distribution systems, including transformers, leading wires, and meters.

Furthermore, combining smart meter data with equipment information about voltage or load current recorded in geographical information systems could enable voltage monitoring of distribution systems and outage monitoring to identify equipment breakdown [6].

Improvement of Planning Power Demand and Supply

After full retail liberalization, electricity retail companies in Japan are required to balance demand and supply every 30 min and must pay a penalty for imbalance. Thus, understanding the demand structure is very important for optimizing power generator management. Therefore, smart meter data could improve the accuracy of forecasting of electricity demand or PV generation. Furthermore, the effectiveness of energy conservation programs could be measured more precisely [7].

Table 1: Data objectives for smart meters

Objectives	Examples
Support for efficient energy use	Feedback or presentation of tips for energy conservation or demand response programs
Support for tariff selection	Proposal of tariff based on forecasted electricity bills
Efficiency improvement of management of end-user appliances	Control of home electric appliances cooperating with HEMS
Supply of new services	Monitoring elderly people, security, healthcare, and product marketing
Improvement of targeting strategies	Segmentation of customers and presentation of customized service contents
Improving management of electricity distribution system equipment	Voltage monitoring of distribution system and outage monitoring to identify equipment breakdown
Improvement of planning power demand and supply	Optimization of power planning, power management, and electricity procurement

Data Analysis Methods

Simplified Disaggregation

The term "disaggregation" usually means a method for estimating what type of electrical appliances are being used from time-series house-wide consumption data, assuming that very fine time-resolution data are available [8]. However, the time resolution of smart meter data is much coarser than the data used for this type of disaggregation. In Japan, smart meters report 30-min data[1]. The quality of information extracted from coarse data is inevitably decreased and estimating energy consumption by appliances from data reported every 15 or 30 min is difficult [9].

To avoid confusion with disaggregation using fine time-resolution data, such as that from HEMS, we call analysis based on smart meter data "simplified disaggregation." Analysis techniques for simplified disaggregation include regression analysis, neural networks, and a "difference method" for defining the between-season demand as "base demand" and the demand exceeding the base demand as "air conditioner demand" [10].

Because each method has merits and demerits, the method that should be used depends on the situation and requirements. Below is an example of scenarios suitable for each method.

1. Computational cost is low and it is easy to understand the output: different methods.

2. High-accuracy estimates are required: neural networks.

3. Between scenarios 1 and 2: regression analysis.

Load Pattern Categorization

Here, we call methods for categorizing electricity consumption data into groups that share similar characteristics "load pattern categorization." Load pattern categorization can be used for dividing multiple households into segments. It can also be used for dividing everyday demand patterns within a single household and grouping them into segments. For this load pattern categorization, clustering techniques are often applied.

[1] In previous research of smart meter data analysis, there are many examples using 30-min data measured in Ireland, which was published by Commission for Energy Regulation (CER). The time resolution of smart meter data is not limited to 30 min, but varies from region to region, and is sometimes aggregated to hourly or daily data.

There are many types of clustering techniques [11]. A review classified these techniques into three types: neural networks, fuzzy logic, and statistical approaches [12]. In particular, self-organizing maps (SOM), which are a type of neural network, are popular. The learning error of SOM's is small [12], and they are effective for mapping data with multiple types of information into two-dimensional space, preserving the similarity between the data as much as possible.

Life Pattern Estimation

There are two types of method for estimating the tendency of the customer to be at home and life patterns: methods using distribution of demand and its variation, and methods using the hidden Markov model (HMM). A typical example is estimating whether a customer is at home. Methods using distribution of demand and its variation include an approach that sorts data in demand order and regards data below a particular percentile as meaning that the customer is not at home [13]. For HMM, being at home can be estimated by detecting the state transition of electricity consumption through monitoring the length of constant electricity consumption [14]. Methods focusing on continuous demand could hold because vacancy occurs for a period of time; for example, daily shopping needs 30 min or several hours.

Attribute Estimation

There are some methods for estimating various attributes of a household or a house itself. One example is that the attributes of 3488 households were estimated from 30-min data by using multiple techniques; the estimated attributes include whether it is a single-person household (two classes), whether the house is over 30 years old (two classes), and total floor space (three classes). The accuracy was reported to be more than 80% in the best cases in two-class problems, such as whether it is a single-person household [15]. Meanwhile, the difficulties in estimating the number of children in a house using 30-min electricity demand data has been reported [16].

Demand Forecast

The targets of demand forecasts range from group-level (such as grid-system-level) to individual-household-level. The methods also range from short-term forecasts for a few minutes ahead to long-term forecasts for a few years ahead. For example, a review article detailed 12 types of approach, including time series analysis, regression analysis, economic models, fuzzy logic, and genetic algorithms [17]. Regression analysis and neural networks are the major methods of forecasting for the next day or the current day.

For forecasting aggregated data on a group-level, computationally expensive methods, neural networks would be suitable because the number of forecasted targets is small. In contrast, regression analysis would be suitable for forecasting individual household-level demand because the number of forecasted targets is large [18]. Generally, fluctuations in individual household-level data are large, and the fluctuations decrease as the data are aggregated on a group level. Therefore, forecast accuracy decreases as the size of the targets approaches an individual-house-level [19].

Table 2: Data analysis methods for smart meter data

Analysis Methods	Main Purpose	Problems
Simplified* disaggregation	Estimate of air conditioner use per time period Estimate of temperature sensitivity	Not suitable for estimating consumption or operating status of individual appliance (detailed disaggregation*)
Load pattern categorization	Categorization of customers based on consumption per time period Detection of anomalous load patterns	Analysis plan suited to the objective is required because categorization is non-unique

Life pattern estimation	Detect whether residents are at home or active	Distinguishing between residents being at home and consuming no electricity and residents being out is difficult
Attribute estimation	Attributes strongly correlated with demand (number in household or floor space) is estimated accurately to some extent	Certain amount of data labeled with actual attributes is necessary for model
Demand forecast	System-wide or area-wide demand forecast Customer-wide forecast	Accuracy decreases in small-scale or long-term forecast

* Data resolution (time etc.) is different (Simplified: 30-min, Detailed：Hz or finer).

Exploratory Data Analysis

This section shows our exploratory data analysis focusing on the combination of simplified disaggregation and life pattern estimation, which are important for supporting efficient energy use in the residential sector.

Table 3: Household attributes

Household	Location	Household size (No. people)	Type of building	Gross floor space (m^2)	Location (AMeDAS)	ID on Database
1	Sagara-gun, Kyoto-fu	4	Detached	70	Ueno, Mie-ken	WEB02
2	Ikoma-shi, Nara-ken	4	Detached	110	Nara, Nara-ken	WEB04
3	Nara-shi, Nara-ken	4	Detached	125	Nara, Nara-ken	WEA04
4	Suita-shi, Osaka-fu	2	Detached	139	Osaka, Osaka-fu	WEA09

We extracted 1-year data from four households in the Kansai area of Japan using the database “Energy consumption for residential buildings in Japan” published by the Architectural Institute of Japan [20]. We converted the data into 1-h data in units of 100 Wh and analyzed them. Temperature data assigned to each household are 1-h data from Automated Meteorological Data Acquisition System (AMeDAS), which gathers regional weather data, close to each location (Table 3).

Analysis Method

This section describes our method for estimating temperature-sensitive demand, including air conditioner demand, by using house-wide electricity consumption and AMeDAS data.

Model Candidates

Three formulae are predefined for regression analysis candidates, and model estimation was conducted for each hour from 12 am to 11 pm.

Model 1 represents the temperature increase and cooling demand increase, or the temperature decrease and heating demand increase as a linear relationship, based on cooling degree hours (CDH) and heating degree hours (HDH).

Model 2 approximates the relationship between the demand change and temperature change by a quadratic function.

Model 3 assumes that there is no temperature-sensitive demand.

Model 1:

$$FDem_{1,d,t} = ACT_{d,t} \cdot (a_{1_t} \cdot CDH_{d,t} + a_{2_t} \cdot HDH_{d,t} + a_{3_t} + a_{4_t} \cdot IN_{d,t}) + a_{5_t} \cdot HL_d + a_{6_t}$$

(1)

$$\left(\begin{array}{l} CDH_{d,t} = \begin{cases} T_{d,t} - 22 \; (T_{d,t} > 24) \\ 0 \; (14 < T_{d,t} \leq 24) \end{cases} \\ HDH_{d,t} = \{14 - T_{d,t} (T_{d,t} < 14) \end{array} \right)$$

t: Time, *d*: date, $FDem_{model,d,t}$: estimated total demand (Wh), $T_{d,t}$: temperature (°C), $CDH_{d,t}$: CDH (°C), $HDH_{d,t}$: HDH (°C), HL_d: holiday dummy, $IN_{d,t}$: insolation ratio (%), $ACT_{d,t}$: demand activity flag dummy

$CDH_{d,t}$ and $HDH_{d,t}$ are differences in the observed temperature from the base temperatures in a given time, *t*, on a given date, *d*. These values are not cumulated like commonly used CDD or HDD, but are recalculated in every time step.

$ACT_{d,t}$, which represents whether the data is demand-active at each time on each day, is a dummy variable determined by the formula below. This dummy is a variable that represents the decrease of electricity consumption caused by being absent from home or at bedtime.

$$ACT_{d,t} = \begin{cases} 1 \; (RDem_{d,t} > Thr) \\ 0 \; (RDem_{d,t} \leq Thr) \end{cases} \quad (2)$$

$$Thr = \frac{\sum_{d \in D} \min_t (RDem_{d,t} + 100)}{366} \quad (3)$$

$RDem_{d,t}$: Actual values of total demand (Wh), *Thr*: threshold for demand-active flag (Wh)

Model selection

Coefficients $a_{1_t} \dots a_{6_t}$ are determined to minimize the least square error of the estimated demand based on 1-year data each hour from 12 am to 11 pm. The model with the highest explanatory power is selected from Model 1-3 each hour. Thus which of the three models was selected differs from hour to hour.

Determination of temperature-sensitive demand

Temperature-sensitive demand (HCDem) each hour is estimated by the formula below. In *model* 2, an increase from the inflexion point is regarded as temperature-sensitive demand. In *model* 3, there is no temperature-sensitive demand.

$$HCDem_{m_t^*,t,d} =$$

(4)

$$ACT_{t,d} \left(a_{1_t}^* \cdot CD_{t,d} + a_{2_t}^* \cdot HD_{t,d} \right) (m_t^* = 1)$$

Examples of Information Obtained by Estimation

Temperature-sensitive Demand

In Figure 1, the estimated yearly averaged temperature-sensitive demand is compared with actual air conditioner demand. The electricity demand data in this analysis was originally published with disaggregated data for eight types of usage [20], with which we compare our estimates.

The estimated results followed the reference data, where air conditioners are rarely used at midnight and in the early morning, and they begin to be used around 5 am, reaching a peak around 7 am (circle in Figure 1). Use decreases, and then peaks again in the early evening.

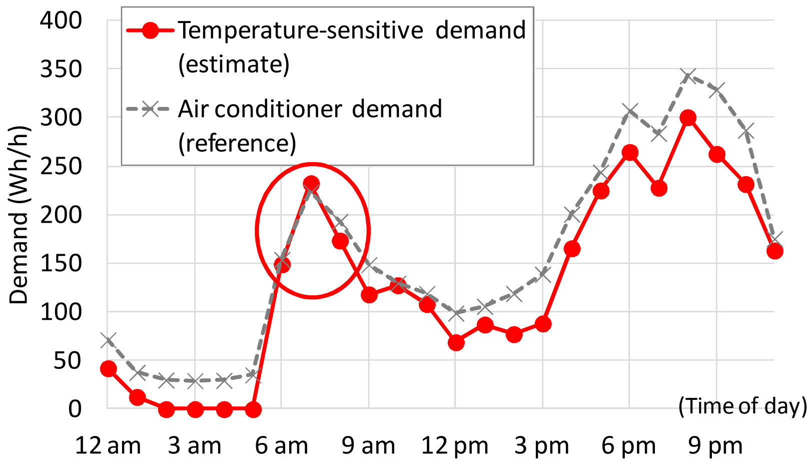

Figure 1: Yearly averaged temperature-sensitive demand and air conditioner demand in household 2

In Figure 2, the estimated monthly summed temperature-sensitive demand is compared with actual air conditioner demand. Although the estimated results are slightly smaller than the actual air conditioner demand in almost all the months, the timing of peaks of both curves is consistent.

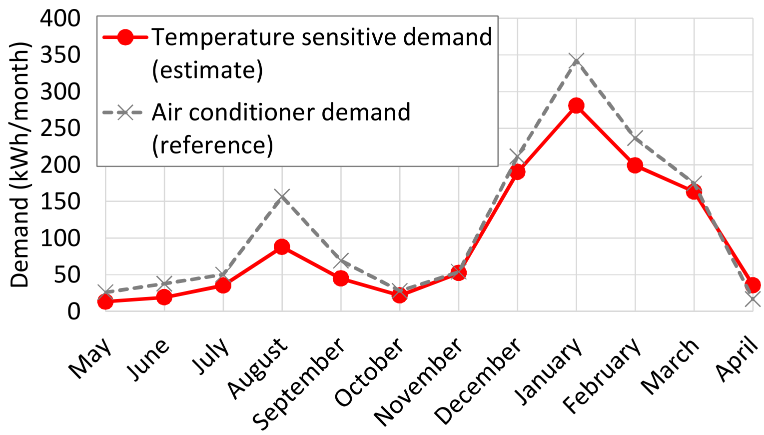

Figure 2: Monthly averaged temperature-sensitive demand and air conditioner demand in household 2

Figure 3 is a scatter plot for demand and temperature for 1-year data for household 1 with the estimated relationship between temperature and demand obtained from the estimated model (red line). The estimated values are substituted into each coefficient and the yearly averaged values are substituted into the explanatory variables except temperature.

Figure 3 (a) suggests that household 2 mainly used heating and rarely used cooling in the morning, whereas Figure 3 (b) suggests that both heating and cooling were used at night. *Model* 1, which uses CDH/HDH, was selected in the morning (8 am), and *model* 2, which uses a quadric function, is selected at night (8 pm), suggesting that model selection functioned properly.

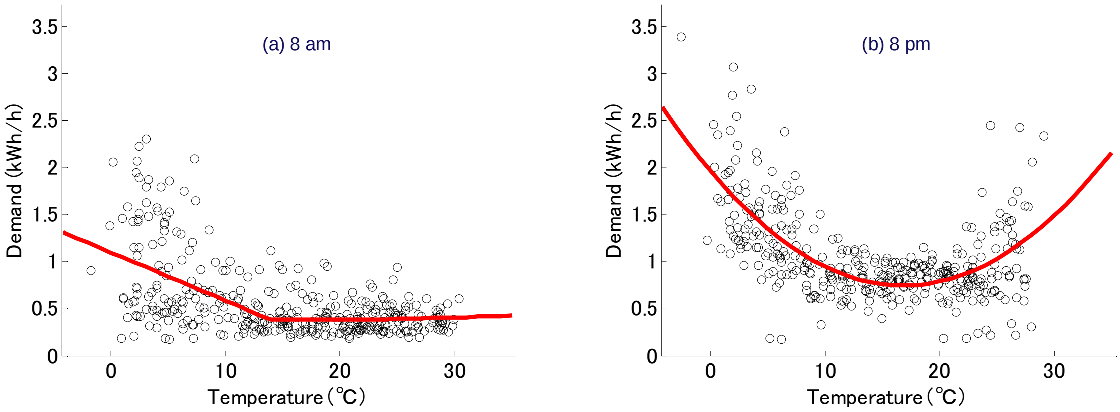

Figure 3: Examples of relationship between demand per time period and temperature in household 2 at (a) 8 am and (b) 8 pm

Demand-Active Level

We define “demand-active level” as the yearly-averaged value of explanatory variable *ACT* which is previously defined binary. This demand-active level suggests frequency of additional demand, except fixed demand caused by such as standby electricity or refrigerators.

Figure 4 shows the demand-active level each hour. All households show a decrease from around 9 am to 2 pm, and increases as evening approaches. The decrease is considered to be caused by people out at work or shopping. However, the patterns of demand-active levels show some variation. For example, the level is lower in household 3 than the other households during the day. In household 2, the people return home around 6 pm because the levels return to almost maximum at this time. In contrast, the people in household 4 return home later than household 2 because the level increases until 8 pm. For midnight and the early morning, electrical appliances, including air conditioners, are rarely used at bedtime in low demand-active level households, such as households 2 and 3. Meanwhile, the level decrease is not observed in households 1 and 4, suggesting that they used air conditioners at bedtime, or stayed up late.

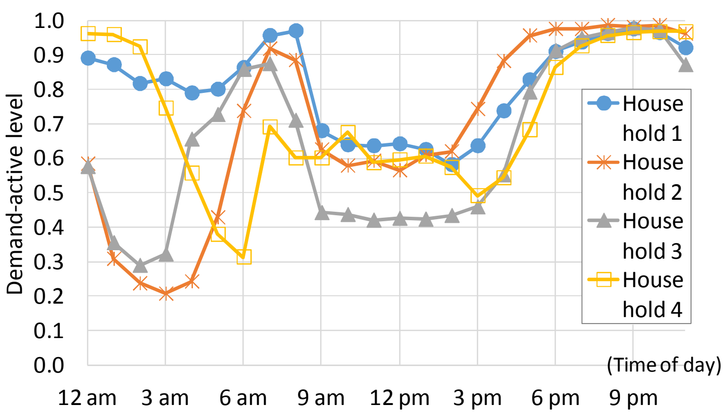

Figure 4: Demand-active level per hour

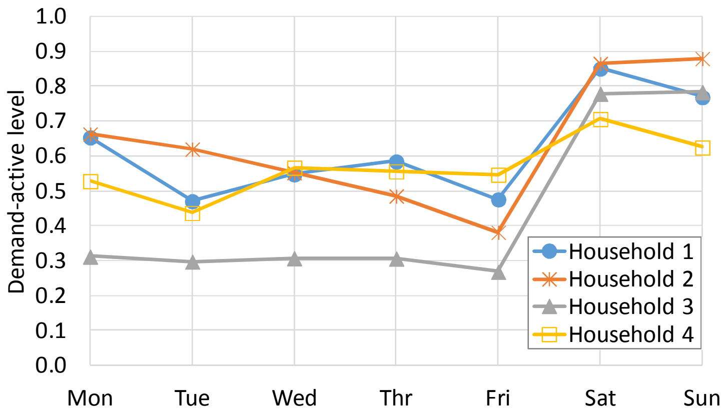

Figure 5: Demand-active level per day of the week for 1 pm to 4 pm (system peak time)

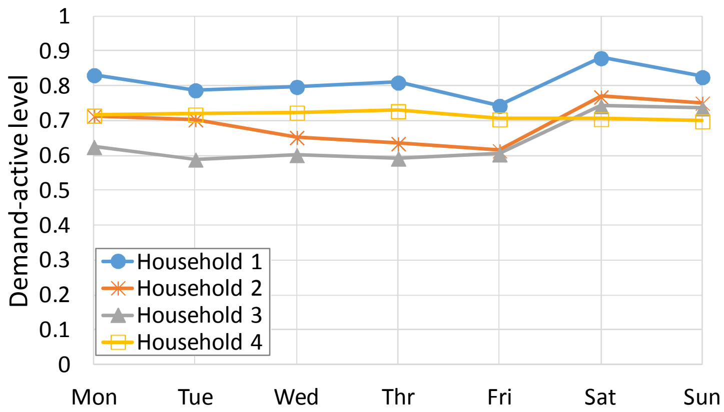

Figure 6: Demand-active level per day of the week for 12 am to 11 pm (whole day)

Figures 5-6 show demand-active level per day of the week for different hours of the day. Identifying the occupancy status at a specific time can improve the effectiveness of information provision by estimating whether the residents are at home and by increasing the arrival rate. For example, 1 pm to 4 pm is when the system demand peak usually occurs in summer in Japan. Thus, DR information for peak demand reduction targeting residents at home at that time may be more effective. Figure 5 suggests that this information may not be effective for household 3 compared with the other three households on weekdays because of the low demand-active level, suggesting that household 3 may be a two-income household. In contrast, at weekends, no large differences were observed in the levels, suggesting that all households could be targeted for information provision on weekends.

Figure 6 shows the level averaged over all the hours of a day. Households 1–3 showed a higher demand-active level on Saturdays and Sundays than on weekdays. In contrast, there was little difference between the weekday levels and the weekend levels in household 4, suggesting that the life pattern of this household did not depend as strongly on whether it was a weekday or weekend. One possible interpretation is that the respondents are retired.

Conclusion and Future Work

Information obtained by smart meter data analysis could be used for behavioral change programs to promote energy conservation behavior. For example, estimating demand patterns for air conditioners could enable targeted energy conservation advice. Another example could be delivering customized advice considering times of a day when each customer is at home and demand-active.

Electricity consumption data is only one of many types of usage data. Although we only used home-wide master switch electricity demand data with Automated Meteorological Data Acquisition System (AMeDAS) data in our explanatory analysis, there are other types of energy demand data including gas and water consumption, or shopping records, such as credit card data. Using such multiple usage data would allow us to obtain better understanding of energy consumption behavior.

For example, if smart phones could operate all electrical household appliances, this framework could produce finer records of the usage of each appliance. This information could identify which appliances consume the most electricity and could help to provide targeted tips for energy conservation for the specific appliance. Another example would be providing advice for the maintenance of old appliances. Combining buying history data on e-commerce sites or credit cards with electricity consumption data could be used to estimate the age of the appliances more precisely. Therefore, it would be important to use electricity consumption data in conjunction with multiple types of data, and to consider the position of electricity smart meter data within the huge variety of usage data available.

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Whole-House Energy Use Across the Pacific Northwest

Bob Davis and Ben Larson

Ecotope, Inc.

Abstract:

A utility meter tells you how much total energy a house uses but not the constituent parts: space conditioning, water heating, appliances, lights, and consumer electronic devices. The recently completed Residential Baseline Stock Assessment Metering (RBSA Metering) project looked beyond the utility meter to measure what, when, and how much energy is used within 100 houses across the Pacific Northwest of the United States. RSBA Metering lasted in excess of two years and monitored energy use at five minute intervals. The study directly measured most energy end uses in houses including space heating, space cooling, water heating, lighting, major appliances, consumer electronics, and other miscellaneous loads. Taking a holistic approach to examining energy use in the house, the paper summarizes findings from the first and second years of monitoring.

The study offers significant insight into the total and individual energy uses in residences and has already proven useful in revising regional thinking. The last regional end-use study was completed over 25 years ago. In the meantime, both energy technologies and measurement techniques have greatly changed. For example, application of compressor-based technologies in both space and water heating can provide large savings. In part, the paper will discuss how an accurate and detailed measurement of electricity usage can afford analytic leverage in putting together both conservation and demand reduction estimates in a large region of the United States. The specific knowledge helps policy makers, designers, builders, and occupants reduce the energy use across all dwellings.

1. Background

As part of the Residential Baseline Stock Assessment Metering (RBSA Metering) project, Ecotope metered appliance energy use in 104 houses in the Pacific Northwest.[1] Sponsored by the Northwest Energy Efficiency Alliance, the study is a subsidiary of the larger regional survey, the Residential Building Stock Assessment.[2] The houses studied were selected randomly from the population of houses in Washington, Oregon, Idaho, and western Montana (see Figure 1). The study began in late 2011 and concluded in late 2014, collecting over 100 GB of data at five minute intervals. Data were collected both at the main house electrical panel and at individual branch circuit termini, allowing direct measurement of both large and small end uses. A detailed description of the metering and data handling system is found in Davis et al.[3] The full report should be referenced for additional insight into the many loads that cannot be discussed here.

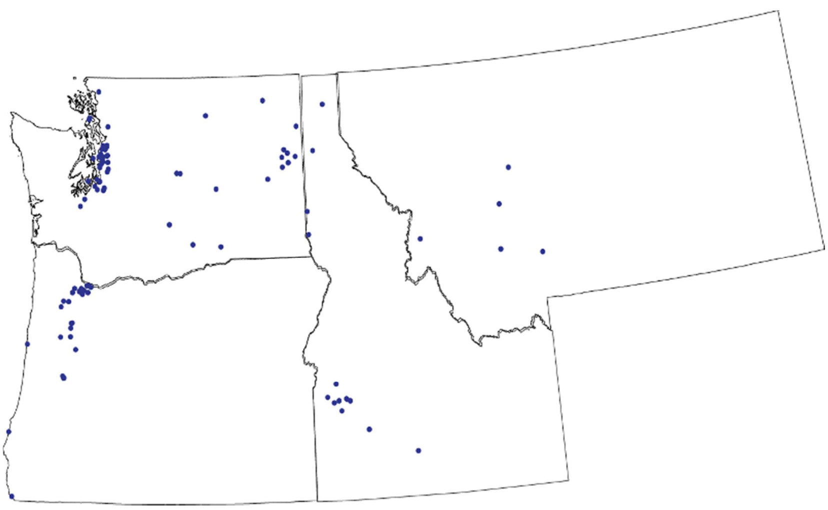

Figure 1. Field Site Locations

Figure 2 shows the breakdown of whole-house electricity usage for the sites that used electricity for both space heating and domestic hot water. Note this figure averages usage across the region so it includes sites in relatively mild parts of the region and sites situated in a more continental climate. On average, mechanical cooling electricity usage across the region averaged about one-tenth of the electricity used for space heating. Also note that, on average, about 15% of the electricity in these sites was not directly metered. (It was not practical to meter all electric end uses at all sites.)

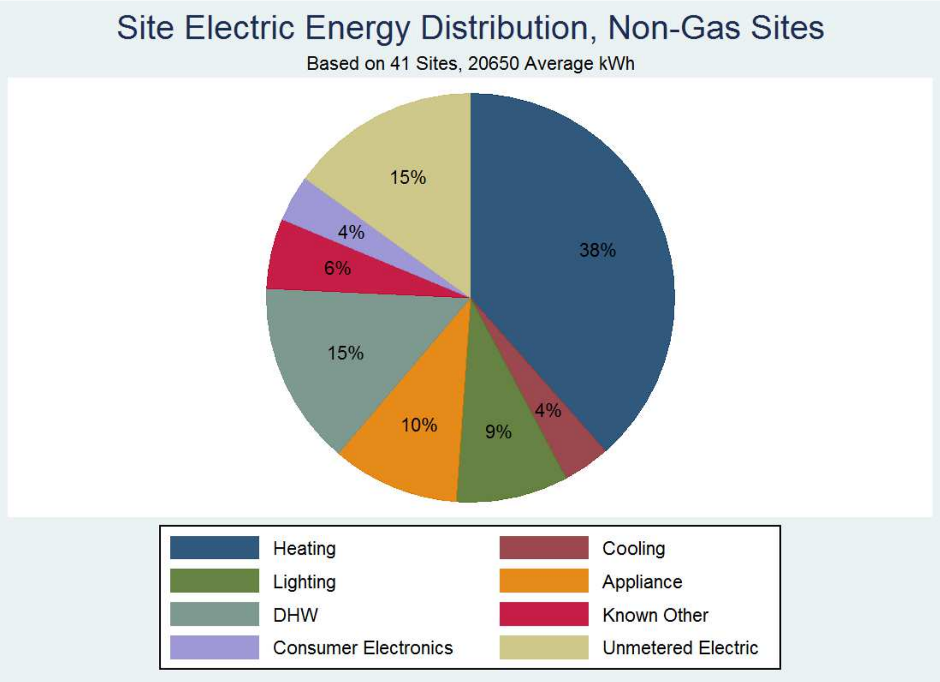

Figure 2. Electricity Usage Breakdown (Electric Heat Homes)

In addition to the total amount of electricity consumed by an end use, its time-of-use is important to power planners seeking to balance supply resources with demand. The five-minute interval measurements show how devices operate at the sub-hourly time scale. Further, the energy uses can be aggregated at hourly, daily, and monthly intervals to show large-scale patterns in appliance usage. In this paper, the usage patterns of selected major appliances (heat pumps, water heaters, and refrigerators) are examined to provide insight into possible conservation and demand-response programs.

2. Heating Systems

Space heating is the largest end use in most Pacific Northwest homes. RBSA Metering heating systems included baseboard (zonal electric resistance), a gas boiler, ductless heat pumps (DHPs), electric forced air furnaces (FAF), gas forced air furnaces, a gas heating stove, and heat pumps. In the Pacific Northwest, about 2/3 of homes are heated by natural gas forced-air furnaces. However, given the project sponsors' orientation and primary emphasis of the research (electricity end uses), more time was spent looking into electric heating system behavior. Table 1 shows the heating Energy Use Intensity (kBtu/ft^2/yr) for each of the major system types. The EUIs here are normalized to the most recent long-term weather data.[4]

Table 1. TMY3 EUI (kBtu/sqft-yr) by Heating System Type

Heating	TMY3 EUI by Heating System Type		
	Mean	EB	n
Baseboard	17.7	3.3	6
Electric FAF	23.4	4.1	7
Gas FAF	29.4	2.3	43
Heat Pump	10.65	1.9	10

Over the past 25 years, Bonneville Power Administration and various electric utilities have attempted to influence the performance of air-source heat pumps that serve central ducted distribution systems by offering various incentives for product selection and installation procedures (especially those that involve control of backup resistance heat). Despite these efforts, heat pump system performance still has room to improve.

An earlier study of heat pump performance found a number of reasons for substandard system performance, inducing undersized (insufficient capacity vs heating load) systems, poor duct performance, and improper control of backup resistance heat.[5] Figure 3 shows an example of this behavior. HP_out is the outdoor unit (compressor) energy and IDT is the indoor temperature, corresponding to the left vertical axis. The HP_in channel, which includes the system air handler and electric resistance elements, displays a marked jump in usage at about 45° F outdoor temperature; this indicates electric resistance heat operates even at that relatively mild ambient condition, reducing the potential benefit of the heat pump system. A review of the house revealed the heat pump was sized to meet the entire heating load down to 35 °F (with allowance for duct losses) but there was no lockout control on the electric resistance heat. These controls are relatively inexpensive to install and would provide both energy and demand benefits. However, their promotion is confined mostly to new installations and therefore, it is not surprising that most of the heat pump systems studied in RBSA Metering did not include them.

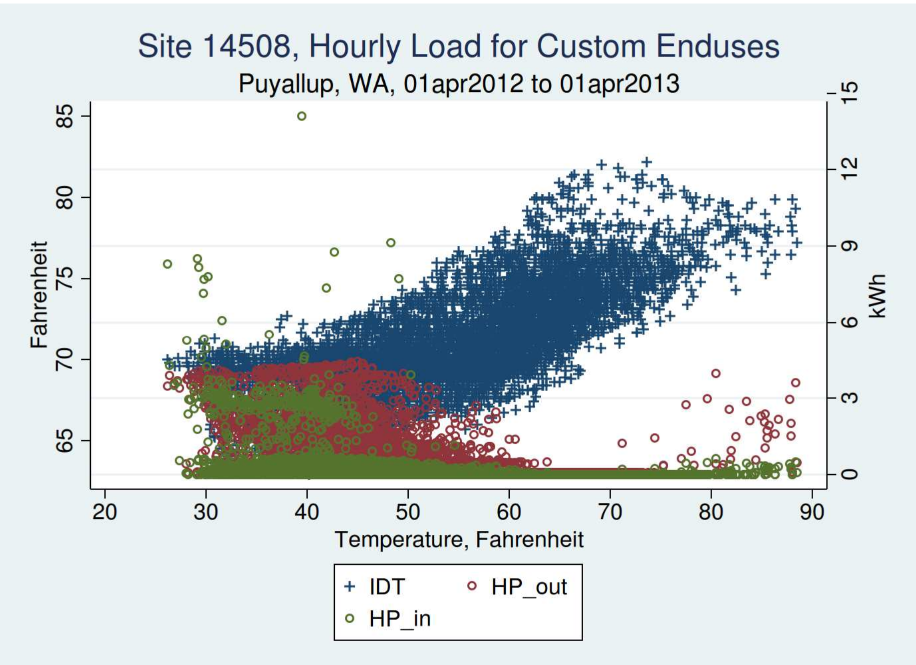

Figure 3. Heat Pump Behavior vs Outdoor Temperature

3. Major Appliance Energy Use

Although the exact saturation varies, appliances are found in various combinations in every house across the country. Appliances represent a significant fraction of the "process" load in residential settings. Indeed, the RBSA Metering study showed the typical mix of electric appliances in houses across the Northwest use 2,300 kWh/yr out of an average whole-house usage of about 20,000 kWh/yr. All appliances are important both in terms of their contribution to overall household electricity use and as potential conservation measures. Accordingly, most of the appliances are already subject to national-level standards. All are important in the characterization of the non-heating/cooling, non-DHW, and non-lighting usage in the home.

The study metered nearly all electric appliances in a house except when data loggers failed to provide usable information. The study excluded metering the small fraction of cooking equipment and dryers that are fueled with natural gas. Table 2 shows the appliances found on site at all of the 104 metered sites, those which were metered, and those that provided viable data for inclusion in the analysis. As Table 2 shows, nearly every clothes washer, clothes dryer, freezer, and refrigerator was metered. A smaller percentage of dishwashers, often due to wiring challenges were metered. The number of cooking ranges found onsite includes both electric- and gas-fueled ranges. Nearly every electric range was metered.

Table 2. Metered Appliance Count

Appliance	Number of appliances		
	On site	Metered	Viable data
Clothes Washer	103	102	97
Clothes Dryer	103	99	93
Dishwasher	93	64	58
Freezer	60	52	46
Range (Electric or Gas)	103	71	63
Refrigerator	133	131	120

For any given site, there is at most one of each appliance except for refrigerators. In the above table, “Freezer” refers to stand-alone appliances whose sole purpose is to freeze food. “Refrigerator” refers to the typical refrigerator-freezer combination (either side-by-side or stacked vertically). In the cases where a house had more than one refrigerator, we designated the refrigerator in the kitchen or pantry area as primary and additional refrigerators as secondary. The secondary refrigerators were most commonly located in garages. “Electric Range” includes energy used both on the range top and for the oven.

Table 3 and Figure 4 place the individual appliances in context by summarizing the annual electricity use of each. The biggest user, well ahead of any other, is the dryer. Electric dryers do have potential for meaningful electricity savings in the next several years as vapor compression cycle based dryers enter into the U. S. market. The next biggest contributors are the refrigerators and freezers; after that come electric range, dishwasher, and clothes washer. All error bounds (EB) reported are for the 90% confidence level.

Table 3. Major Appliance Yearly Usage (averages)

Appliance	Annual kWh		n
	Mean	EB	
Clothes Washer	55.0	5.2	97
Clothes Dryer	724.9	54.6	93
Dishwasher	238.7	36.8	58
Freezer	608.8	59.9	46
Electric Range	313.9	34.7	63
Primary Refrigerator	604.4	24.8	99
Secondary Refrigerator	600.0	109.7	21

Average number of occupants: 2.7
Average number of bedrooms: 3.1
Average site floor area (ft^2): 2,145

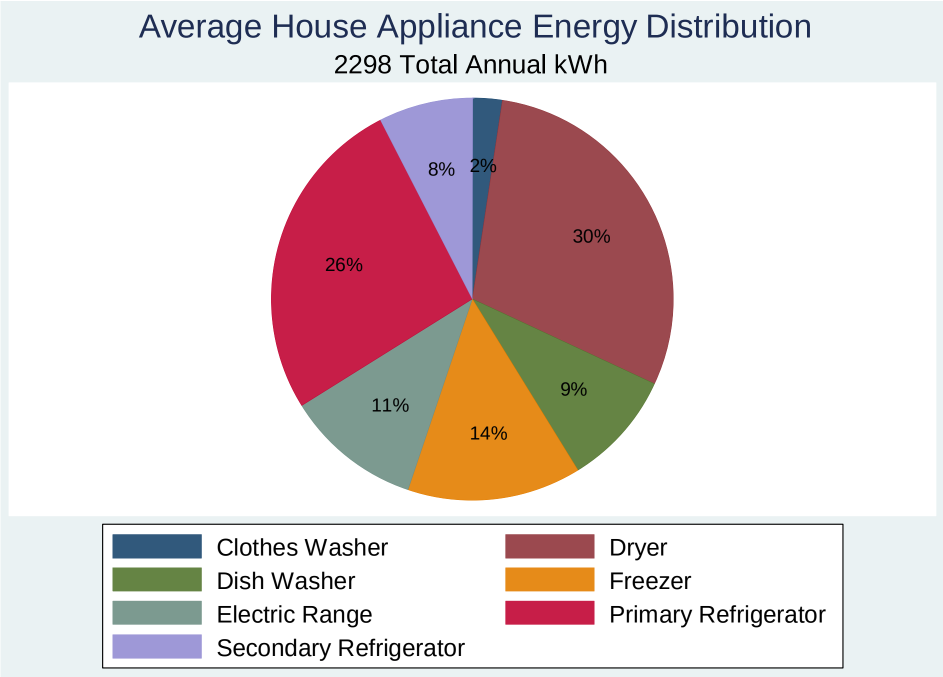

Figure 4. Major Appliance Electricity Usage Profile

3.1 Refrigerator and Domestic Hot Water Load Shapes

Major electrical appliance load shapes are of interest because of the possibilities for both energy and peak load reduction. Because of space limitations, we will confine detailed discussion here to two end uses: refrigerators, and water heaters. These end uses are ubiquitous and significant in all houses and a detailed look into their behavior provides valuable insight for ongoing efforts to improve efficiency and consider demand response measures.

3.1.1 Refrigerators

Refrigerators are found in almost all homes and represent a significant fraction of annual appliance energy usage (as shown above). Residential refrigerators and freezers have undergone three federally mandated efficiency upgrades in the United States, one each in 1990, 1993, and 2001.[6] Figure 5 shows the expected downward trend in annual energy use implied by the ever more stringent standards. The figure plots energy for both primary and secondary refrigerators while the regression fit is conducted only on the primary refrigerators. Although site-to-site variation is high, the slope of the fitted line is -13.5 kWh/yr, suggests in a 20-year time period, refrigerator energy use has decreased 270 kWh on average. This has happened despite an increase in average refrigerator interior volume.

The classification of primary and secondary refrigerators is of importance regarding the ambient temperature surrounding the equipment. Although we can reasonably assume the temperature in living spaces is similar across houses, the temperature in secondary locations, such as garages, varies more widely and, in the Northwest, is annually lower on average than the living space. A substantially different average ambient temperature will lead to different energy use of a refrigerator. Without a sample size large enough of secondary refrigerators to control for temperature, we conducted all the comparisons on primary refrigerators only.

Other factors influence the annual electricity usage, such as occupant preferences and kitchen temperature, but even with all these considered, we see a downward trend in the averages, indicating that the standards have been largely effective in reducing energy consumption. The results also indicate that, to the extent older equipment is still being used, there is potential for significant savings through utility-based programs.

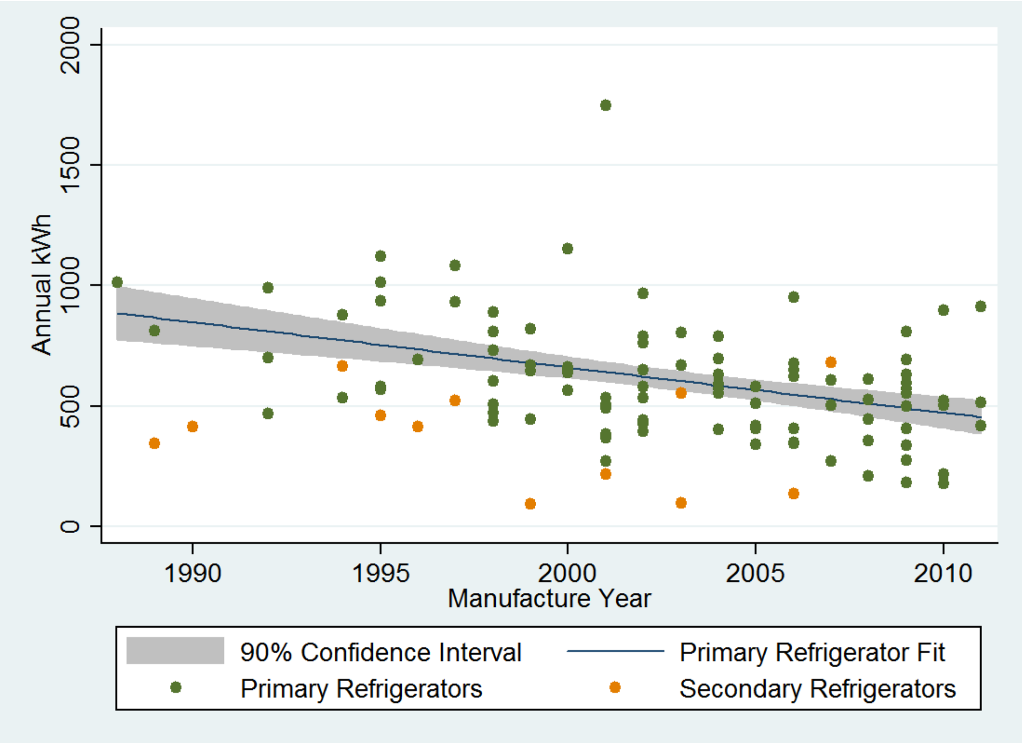

Figure 5. Annual Refrigerator Energy Use by Year of Manufacture.

Within a day, the average hourly refrigerator power draw exhibits slight variations (Figure 6). As expected, the usage decreases in the night-time hours, given that the space containing the refrigerator likely reaches its daily minimum and door opening events are curtailed. The usage peak in the evening is due, in large part, to occupants placing warm food items in the refrigerator. An investigation of the average energy use by day of week shows a flat line with no dependence on weekdays or weekends.

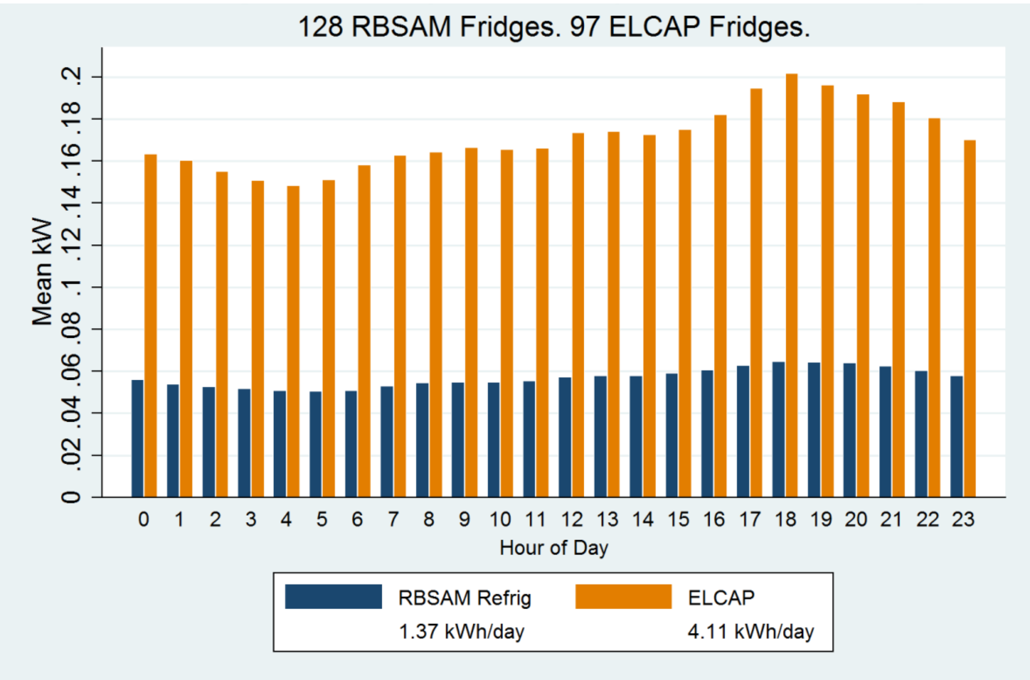

Figure 6. Daily Refrigerator Load Shapes: Historic Comparison

A comparison of current residential refrigerators with those installed in the Pacific NW at the time of the last end- use study also shows the stark difference in peak demand (Figure 6). Newer systems have much better insulated cabinets and compressors greatly reducing the load profile. The ELCAP abbreviation in Figure 6 represents the previous end use study.[7] Refrigerators in the old dataset dated from the late 1960s through late 1980s. On average, the newer equipment indeed has half the demand of the old.

Metering energy use at a five-minute time scale reveals load patterns that can be useful in demand response programs. For example, Figure 7 shows the power measurements of two refrigerators, each in a different house, for two days in the summer. Both are located in kitchens and have a volume of 20 ft^3. Refrigerator A was manufactured in 1995, while B was in 2006. Although both refrigerators show a typical cyclic behavior, a demand response opportunity lies in the defrost control. Both pieces of equipment have automatic defrost, which is indicated by the spike in power to 800 W (in blue) and 425 W (in red). They defrost as needed but do not repeat at any obvious frequency. Post-defrost, both compressors run for a longer period of time, presumably to reduce the interior temperatures after the defrost cycle. A simple control could be conceived to restrict the times when the defrost cycle occurs to off-peak hours, thereby reducing peak demand from both defrost and recovery events.

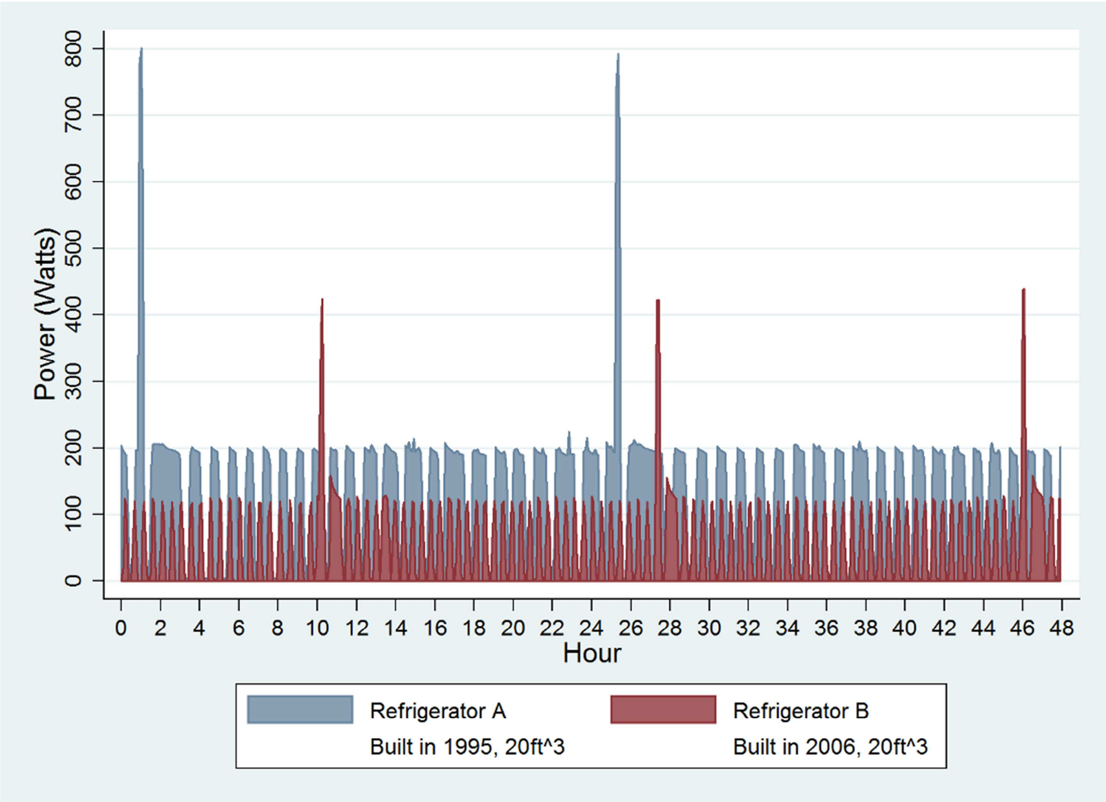

Figure 7. Detailed Typical Refrigerator Power Patterns. (Two days beginning midnight 7 July 2012.)

3.1.2 Water Heating

Domestic water heating is the second largest load in most Pacific Northwest houses. In this region, 55% of the 4 million households use electricity to heat domestic hot water (DHW).[2] The dominant technology consists of electric resistance elements in an insulated tank. The main drivers in reducing water heating load have been flow-rate reductions and improved tank insulation. Table 3 summarizes the net effect of the improved insulation level and reductions in hot water use through lower flow-rate fixtures and appliances; these data are from the main RBSA report.[2] Note average number of occupants per household served by an electric tank is relatively stable between the two data sets (about 2.6 in the older dataset and 2.7 in the newer). Also note the inventory of different tank sizes is enumerated; this has significance for changes in United States federal standards for water heaters; namely, tanks over 55 gallons will have to use a compressor to heat water beginning April 2015.[8] This issue is discussed further on in this section.

Table 4. Hot Water Heater Regional Data (historic comparison)

Parameter	1990 dataset (ELCAP)	2012 dataset (RBSAM)
Annual use (kWh)	4,700	3,000
Savings/unit (kWh)		1,700
Water heater stock ≤ 55 gal	2,701,101	3,489,689
Water heater stock > 55 gal	300,122	337,815
Water heater stock (total)	3,001,223	3,827,504
Annual load (aMW)*	1,610	1,311
PNW 2012 savings (aMW)		299
Coincident peak load (MW)	2,941	2,034
Coincident peak savings (MW)		907

*average Megawatt

The summary data from the table show the dramatic reduction in grid energy needed for the domestic hot water load; they also point out the large reduction in peak savings even with more tanks on line vs 1990. Figure 8, informed by Eckman (2014), illustrates the change in weekday peak on a system-wide basis.[9] Note the time of the morning peak is relatively similar but it appears the evening peak has drifted by at least a few hours in 25 years. Work and commuting patterns have likely changed over that time. However, despite the increase in the number of water heaters, the overall peak demand has decreased.

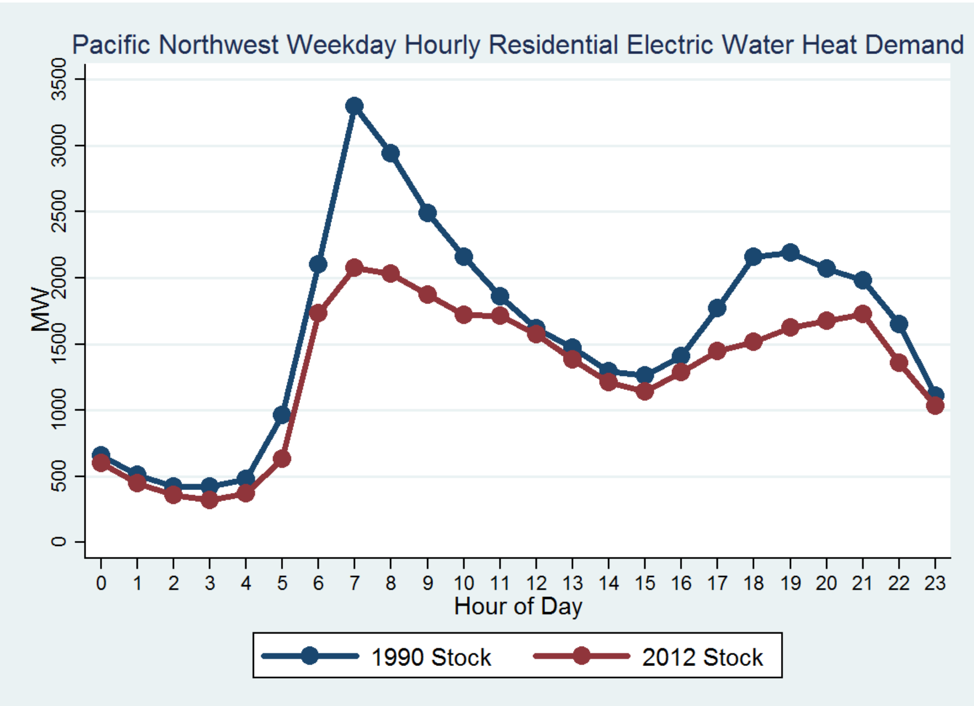

Figure 8. Aggregate DHW Demand Profile, ELCAP (1990) and RBSAM (2012)

Reductions in energy use through lower flows and more insulation, while significant, are likely close to their limit. As such, the next round of substantial gains in electric water heater efficiency is only available with different heating methods. The "bottom line" requirement for these systems is that they can deliver enough hot water for households while doing so with at least an annual Coefficient of Performance (COP) of 2 so that the higher cost of the unit versus an electric resistance tank will be paid for over time by the increased efficiency.

Recent research has focused on a targeted push to bring to market a HPWH that will deliver adequate hot water when relying on intake air from a northern climate; most HPWHs sold in the United States have thus far been designed to deliver water at COPs of around 2 only in middle and southern latitude climates.[10] By using the results of RBSA Metering for resistance tanks and overlaying the measured field performance of a set of HPWHs on the same graphic, one can see what the next increment of efficiency can offer, at least on a peak demand basis (Figure 9). Peak loads for the HPWH technology are less than a third of what was found in the 1990 ELCAP study.

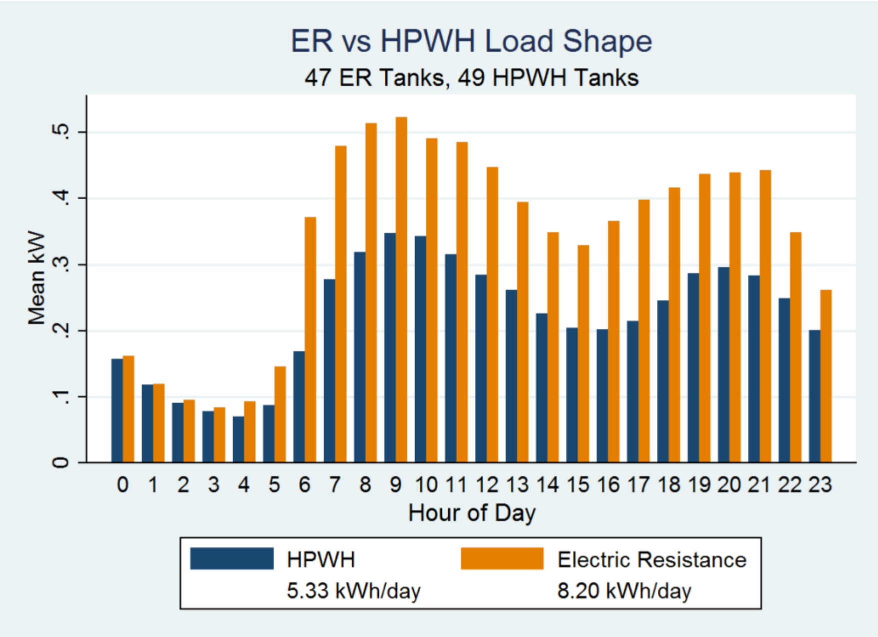

Figure 9. Demand Reduction Profile for Heat Pump Water Heater

Table 5 shows overall effects of the upcoming Department of Energy (DOE) standards change from converting from the newest electric resistance tank technology to the current HPWH technology available in the Pacific Northwest. The coincident peak savings are relatively small in this comparison, given they only apply to larger electric tanks. This is because the new standard, effective April 2015, will only apply to the larger tanks. This standard will only allow heat pump water heaters to heat water in electric tanks larger than 55 gallons.

Table 5. Near-Term Heat Pump Water Heater Savings Potential in Pacific Northwest

Parameter	2012 Electric Tanks	2012 Heat Pump WHs
Annual use (kWh)	3,000	2,000
Savings/unit (kWh)		1,000
Water heater stock >55 gallons	337,815	337,815
Annual load (aMW)	116	77
PNW 2012 savings (aMW)		39
Coincident Peak Load (MW)	174	108
Coincident Peak Savings (MW)		66

The final graphic in the section, Figure 10, shows the weekday hourly comparison of the 1990 tanks and the current HPWH technology. It almost goes without saying that there has been quite a change in the way water can be heated in 25 years. Moreover, research on heat pump water heaters in residential applications has really barely begun; one should expect a lot more to come along in the next few years.

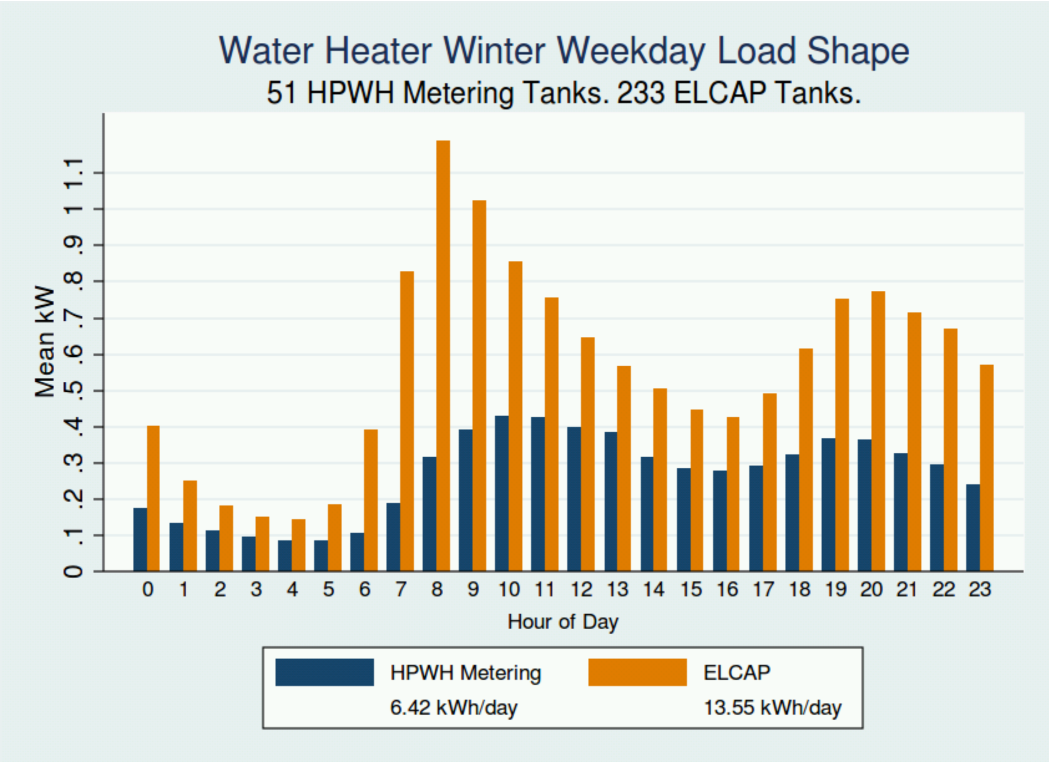

Figure 10. Net Hourly Load Shape Effect: ELCAP (1990) to Heat Pump Water Heater

4. Lighting

Measuring the electricity usage of lighting fixtures presents several challenges: budget constraints often limit the number of lamps measured per house; and lighting loggers, even when carefully deployed, are susceptible to attrition, unknown time drifts, and false readings from ambient light sources. In this study, great care was taken to identify and correct measurement errors, while estimation techniques were employed to extend results to cover unmetered fixtures. By measuring on-time of a sufficiently large number of fixtures in different room types in the test sites, and by employing data from a large parallel RBSA study of Northwest houses, it was possible to build a robust estimate of whole-house lighting energy usage and lighting power density (LPD).[1,2]

The whole-house electricity consumption for lighting averaged nearly 2,200 kWh/yr for the RBSA Metering group. When adjustments were made to account for fixture counts and fixture/lamp types in the larger set of RBSA houses, the Pacific Northwest regional lighting usage was estimated to be 1,970 kWh/yr per house. The LPD (total installed lighting Wattage in the house divided by conditioned floor area) for the Northwest is 1.4 Watt/ft^2. Given the rapid adoption of LED lamps and concurrent changes in national lighting standards, LPDs will continue their downward trend.

The overall lighting load shape is based on the aggregate on-time from the metered sample. It is important to note that the electricity usage associated with this load shape is extremely mutable given the rapid change in lighting technologies. That said, the pattern of lighting *on-time* is expected to remain constant by room and fixture type over a day, month, or year. Thus the load shape shown in Figure 11 is expected to retain its form regardless of the efficiency of the particular lamps installed.

The overall load shape varies by time of day and season of year. In Figure 11 the minutes of on-time per hour over the course of a day is presented as a series of monthly results. For a given hour of the day, there is an on-time difference of up to a factor of 2 between the maximum daylight hours of summer solstice (June and July months) and the minimum daylight hours of winter solstice (December and January). The difference in total daily on-time between the summer and winter solstices is a function of building latitude. Those in this study averaged 46° North latitude. Lower latitudes will have a smaller seasonal variation. Regardless of season, the peak lighting use is in the evening with a second, lower peak in the early morning hours. As the seasons vary from summer to winter and back, the evening peak shifts earlier in the evening from 9:00 p.m. to 6:00 p.m., while the morning peak stays relatively stable between 7:00 a.m. and 8:00 a.m. Note that all the times are reported in local time at a given site regardless of time zone or daylight savings time.

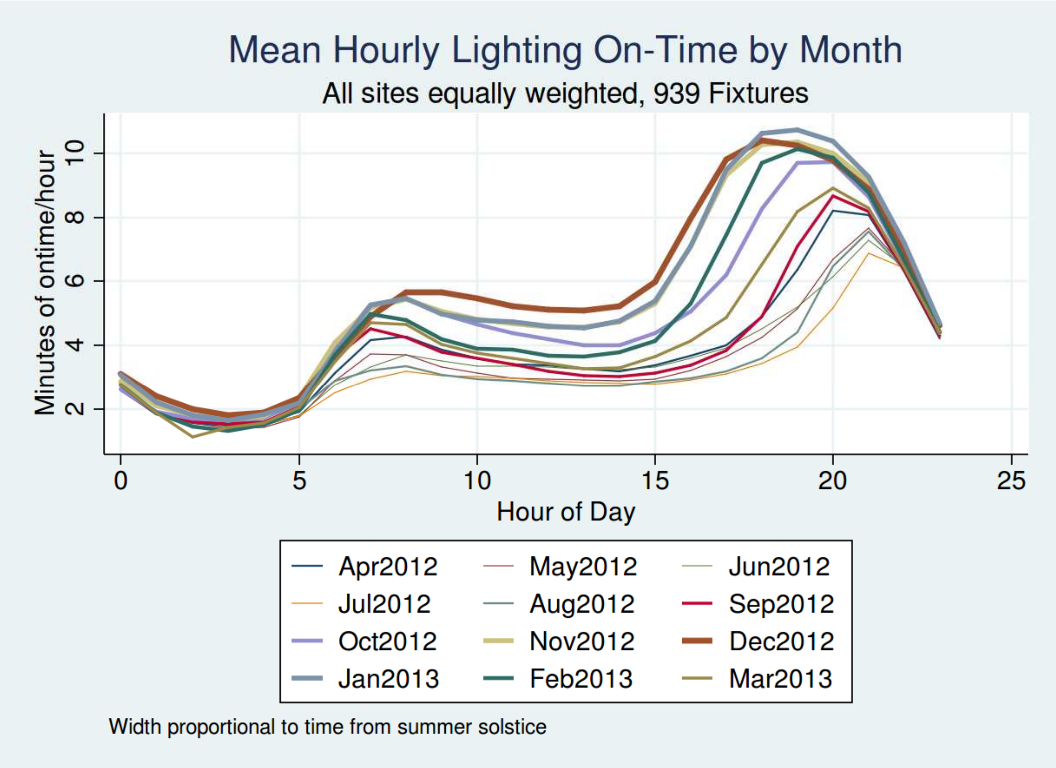

Figure 11. Seasonal Variation in Residential Lighting Fixture On-Time

5. Conclusion

Recent research in the Pacific Northwest of the US has included detailed end use metering of about 100 homes. The data collected from this study have proved quite useful, both in terms of quantifying annual usage and in providing much more detailed characterization of the end uses. The last study of this sort was performed more than 25 years ago, and the tools and techniques available for data collection and analysis have afforded considerably more insight into usage patterns.

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Lessons from a decade of efficient product market analysis

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Abstract

In the last ten years, Topten guides have been developed in a growing number of countries, notably in the EU. These on-line tools provide consumers with precise information about the most energy efficient products they can find in shops, for a wide range of categories. The Topten international network has been successfully expanded thanks to the support from private and public bodies, including the EU Intelligent Energy Europe programme.

The first Topten websites have now accumulated a long experience about the way the market for efficient products has evolved until now, in an interesting context of dramatic changes brought both by new technologies and regulatory decisions (such as the adoption of EU Ecodesign and Energy labelling measures).

Some of the European Topten teams have decided with this paper to look for the first time through the rear-view mirror and provide insightful analysis based on the detailed market data they have gathered since 2008 on five main product groups (refrigerators, freezers, washing machines, dishwashers, TVs).

The analysis includes France, Germany and Switzerland, and investigates the way the best products have evolved across the years, potential country differences in efficient product availability, and implications for consumers of choosing top efficient products.

Lessons can also be drawn on the adequacy of regulatory measures such as the levels of the EU energy labelling classes adopted in the last years.

Background

The Topten programme

Topten is an international programme to create a dynamic benchmark for the most energy efficient products, and hence contribute to transforming the market towards less energy consumption [1]. Its main activity is a network of national on-line guides informing consumers about the most energy efficient products available on the market. On Topten websites, the actual best models in several product categories are presented in detail (brand, model name, picture, main characteristics, price, etc.); they correspond to real products for sale (not prototypes).

Topten has started activity in Switzerland in 2000, and has expanded to other countries (France in 2004, Germany in 2005, etc.). The network now involves 16 European countries, as well as China. Through their daily work, the teams in charge of Topten guides monitor appliance markets, technological trends, as well as regulatory decisions affecting energy-using products.

European Topten websites attracted more than 2 million visitors in 2014 (notably 410,000 in Switzerland, 207,000 in Germany, and 150,000 in France [2] - the three countries on which this paper focuses). There is growing evidence of the potential of these guides to change purchasing behaviours, as illustrated by a visitor survey suggesting a possibly significant level of influence on respondents [3].

2005-2015: a critical decade for product efficiency

After the introduction of energy labels on some appliances in the 90's, the EU has taken long before accelerating its portfolio of policy measures to increase the energy efficiency of products. With the adoption of the Ecodesign Directive in 2005 and a new Energy Labelling Directive in 2010, a new phase began ten years ago. Preparatory investigations and regulatory interventions have multiplied on many product categories. As of February 2015, about 40 Ecodesign and new Energy Labelling measures are in place covering a wide spectrum of equipment.

In the meantime, energy efficiency has gained higher visibility and interest driven by both policy agendas and concerns about energy prices and security of supply. In response, efficient technologies have been boosted. As an illustration, the lighting and TV sectors have been revolutionised in the last decade by LED developments.

An interesting question is the concrete impact of these technological and policy trends on the availability and deployment of more efficient products on the market.

This paper aims precisely at providing insights based on the data collected by Topten throughout the years on the evolution of the top of the market.

Methodology

The findings presented in this paper are using statistics on data collected by Topten guides along the years. Topten informs about the products at the top of the market, identified through strict selection criteria. These criteria are country-dependant and adjusted according to the state of the local market. They are also adjusted over time, and when new regulatory tools are available (such as new top energy labelling classes). The number of products selected in each category or sub-category is typically around ten, but may vary depending on the criteria.

It is important to note that these statistics relate to a very small and specific portion of the products on the market. *The trends and findings are strictly limited to this portion, and are in no way representative of the entire market*. Extrapolations should be avoided. In addition, the statistics are purely model-based and not sales-based (Topten does not collect sales data).

Our analysis covers three pioneering countries for Topten: France, Germany, and Switzerland, where Topten guides have been launched a long time ago so that historical data have a sufficient timespan. This sample of three countries may not be typical of all EU Member State situations, yet it is interesting for the following reasons:

- Substantial differences in residential electricity consumption between France and Germany have been reported, with some difficulties to explain the entire gap [4]. It is therefore useful to check whether there are strong differences in the availability or affordability of top efficient products between these two markets that could be part of the reason.
- Switzerland can be seen as close to both France and Germany, however they are outside the EU so they have some flexibility to set their own efficient product policies that can differ from the EU ones. Examples are more stringent minimum energy performance requirements for cold appliances and tumble driers, and energy labels for coffee machines.

- There is a growing seller concentration in the European appliance sector. Manufacturers are in theory able to sell the same models quite everywhere on the continent. It is interesting to check whether they apply differentiated national marketing strategies with respect to very efficient products.

The analysis covers a 7-year period from 2008 to 2014. 2008 is the oldest date for which sufficiently comprehensive and comparable data could be collected from the three national Topten guides. Incidentally, it also corresponds to the beginning of the publication of the first EU Ecodesign and new Energy Labelling regulations. Topten selections are typically updated twice a year, sometimes once; hence, the statistics presented here are based on one or the average of two sets of data per year.

We have chosen to present findings for five large household appliances: **fridge-freezers, stand-alone freezers, washing machines, dishwashers, and TVs**. Together, these products represent a large share of the electricity consumed by products in homes (typically half or even more). In order to guarantee sufficiently meaningful comparisons, we have restricted the scopes to the following product types:

1. **Fridge-freezers** include only compression-types with two doors ('combined', '2-doors', and excluding American fridges), both integrated and non-integrated
2. **Freezers** include upright freezers only (excluding very small ones such as 'table top')
3. **Washing machines** are front loading ones (all capacities)
4. **Dishwashers** are integrated ones with a width of 60 cm or more (excluding models in the 45 cm range)
5. **TVs** are those with a diagonal in the range 80 to 89 cm. (TV energy consumption is so much size-dependent that it was necessary to restrict the size range for our analysis).

In the analysis, we are using annual energy consumption values as declared by manufacturers and collected by Topten teams to reflect the energy performance of products. Annual energy consumption values are based on standardised duty cycles and measurement methods and are indicated on EU energy labels. It is an interesting indicator, because it captures both technical efficiency and size/capacity aspects of products.

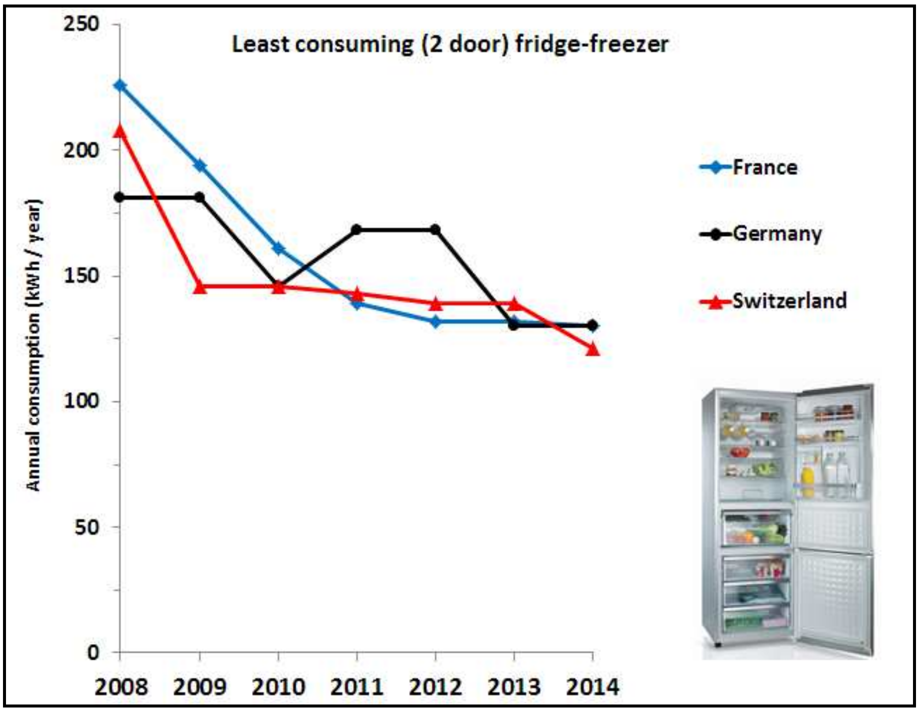
Notes:

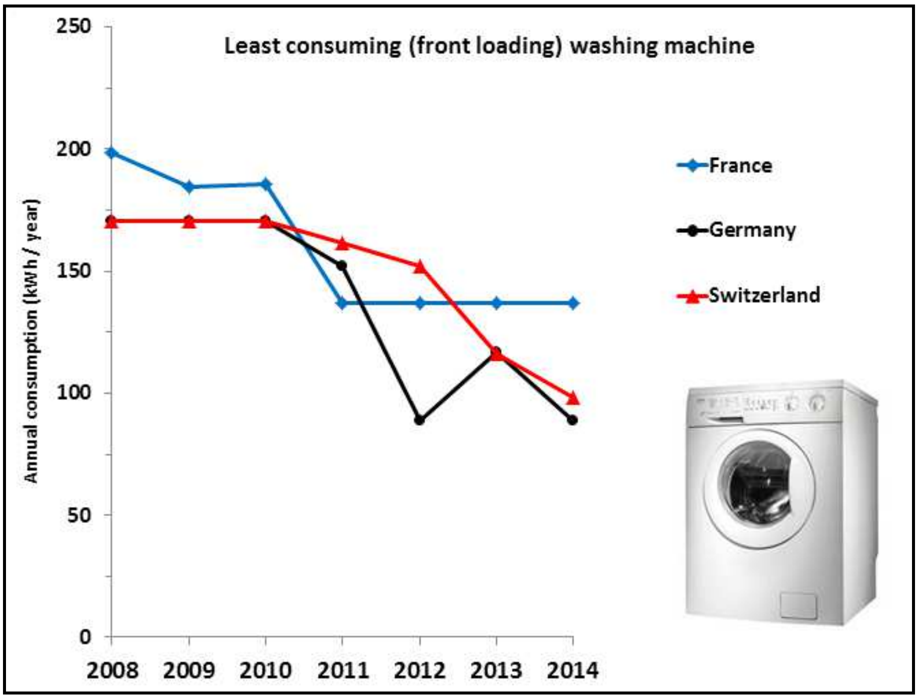
- For washing machines, the EU has introduced in 2010 a substantially new method to test and assess product energy performance. The energy consumption figure is no more based on a simple 60°C full-load cotton programme, but a mix of three programmes (60°C full-load, 60°C half-load, and 40°C half-load) over 220 annual cycles. Standby consumption has also been added. To allow better comparability, we have adjusted the consumption values prior to 2011 accordingly[1]. However, this remains rough and comparisons before and after 2011 should be taken with precautions.
- Similarly, data for dishwashers prior to 2011 have been adjusted to reflect the regulatory assumptions used in the new EU energy labelling measure (duty cycle of 280 washes per year, and a standby consumption).
- For TVs, new testing conditions have been introduced in the EU in 2010 to underpin the energy labelling of televisions. In particular, it has been specified that TV sets should be tested in a 'home mode' and not in another potential brighter mode. This change may have resulted mechanically in lower declared values (a 30% apparent improvement according to the industry [6]). However, we have decided not to artificially adjust our data. Comparisons to figures prior to 2009 should therefore be considered with precaution.

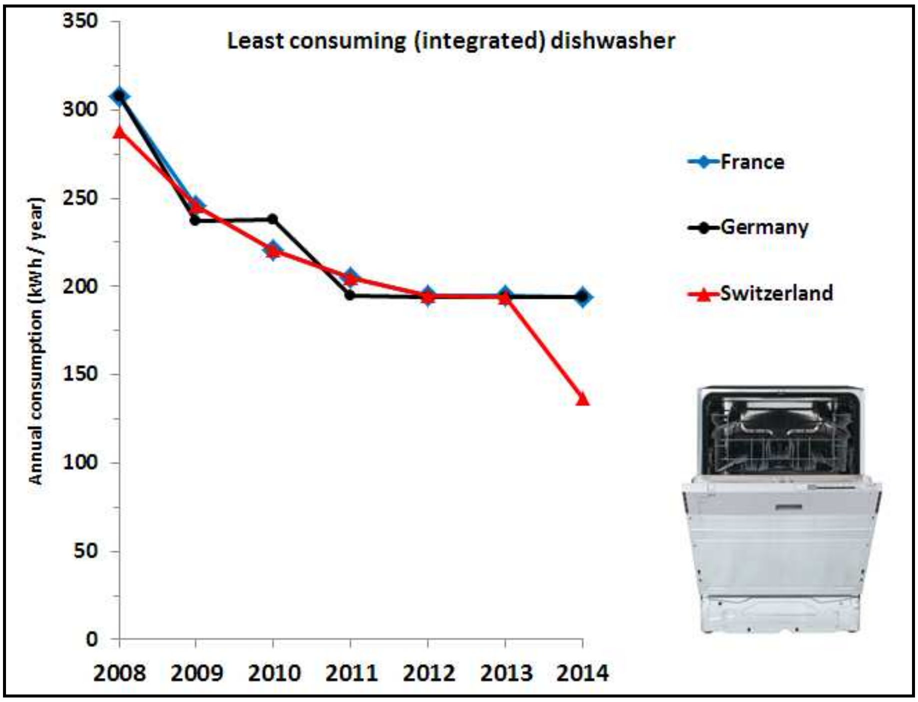
[1] This has been done by considering that the energy consumption of a 60°C half-load programme is 0.8 that of a full-load 60°C and the consumption of a 40°C half-load 0.64 that of a full-load 60°C, and by adding 12.5 kWh of annual standby consumption. These theoretical values are those that the European Commission recommended in 2009 for transitioning between the old and new methods [5].

Findings on top performer trends

We are presenting in this section the evolution of the performance of the top #1 product on the market (the model consuming the least energy in the Topten selections) for four of the product categories and for each of the three countries. This data provides an idea of the pace of innovation and efficiency breakthrough in the last 7 years.







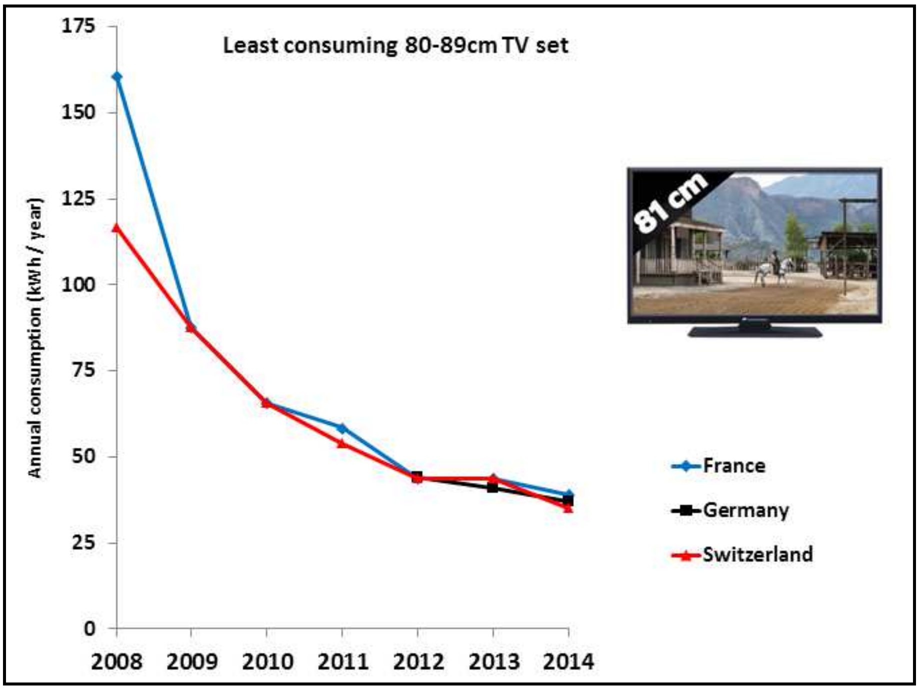


Figure 1-4: Annual energy consumption of the least consuming product model in Topten selections for France, Switzerland and Germany[2]

In 2008 (starting point), Switzerland and Germany had usually some relatively less consuming models on their market than France.

For all product types and all markets, there has been a very strong progress between 2008 and 2014 with **25% to 50% less consuming products** placed on the market. And this dramatic change at the top of the market has taken place despite opposing trends that may increase the annual consumption

[2] Note: for TVs, the data collection in Topten Germany only started in 2012.

(such as increasing capacities, more sophisticated functionalities, etc.). It is interesting to note that the least energy consuming models may be of various sizes and not systematically the smallest ones on the market.

The progress is however not linear. It has been very steep between 2008 and 2012, and it appears to be more in a sort of stabilisation trend since then. One explanation may be the high costs to reach further efficiency levels. Another tentative explanation for white goods lies in the EU policy dynamics: between 2008 and 2010, old and obsolete EU energy labels have been updated with the introduction of additional classes allowing manufacturers to differentiate again. This has been a strong push to place on the market a lot more efficient technologies and innovations, some of which they probably already had in store but couldn't promote beforehand. Now that the new highest class A+++ has been reached as well, there is less incentive for manufacturers to continue placing more efficient products on the market right now.

In 2013 and 2014, for most product categories the country differences appear limited. It means that the best technologies are evenly available across the three markets. This can be the result of a greater single market integration and concentration in the appliance sector. There is a significant exception for washing machines though. France seems late compared to Germany and Switzerland.

Concerning policy aspects, it is striking to see how quickly instruments such as new energy labels put in place in 2010 have been overshot by market evolutions:

- The best fridge-freezers on the market in 2008 were in the A++ class; in 2014 they were exceeding the highest A+++ threshold by 25%.
- The best washing machines in 2008 were in the A+ class (although the grade did not exist officially); in 2014 they were exceeding the highest A+++ threshold by 50%.
- The best dishwashers in 2008 were in the equivalent of class A+; in 2014 they were exceeding the highest A+++ threshold by 40%.
- The best TVs in 2008 were in the equivalent of class D or E; in 2014 they were in class A++ already.

It reflects both that technological progress has been sustained during the period, and that the setting of the new energy labelling classes has been insufficiently ambitious to last long enough.

Figure 5: A manufacturer promoting an 'A+++-50%' model

Impact at household level

In the previous section, we have seen that substantially more efficient products have been placed on the EU market between 2008 and 2014. In the meantime, EU Ecodesign regulations have been adopted to ban from the market products that were not able to reach a certain level of energy efficiency. A legitimate question is then: how far is it still interesting and useful to purchase Topten models instead of standard ones? What difference does it make?

A way of answering this question is to compare the consequences for a household of buying Topten-recommended instead of low-end products at different points in time. We have chosen to show the results for 2008 and 2014 for the five product groups.

The average of products recommended in the Topten selections in each of the three countries is compared to what is called *'non-recommended'* products; these correspond to low efficiency products that can be found on the market and are used in Topten guides as a point of comparison - they are very close to the least efficient level that is available or allowed on the market. For simplicity, we have considered the same set of non-recommended products for the three countries (assuming that the market bottom is comparable; the levels indicated are those from references collected in France).

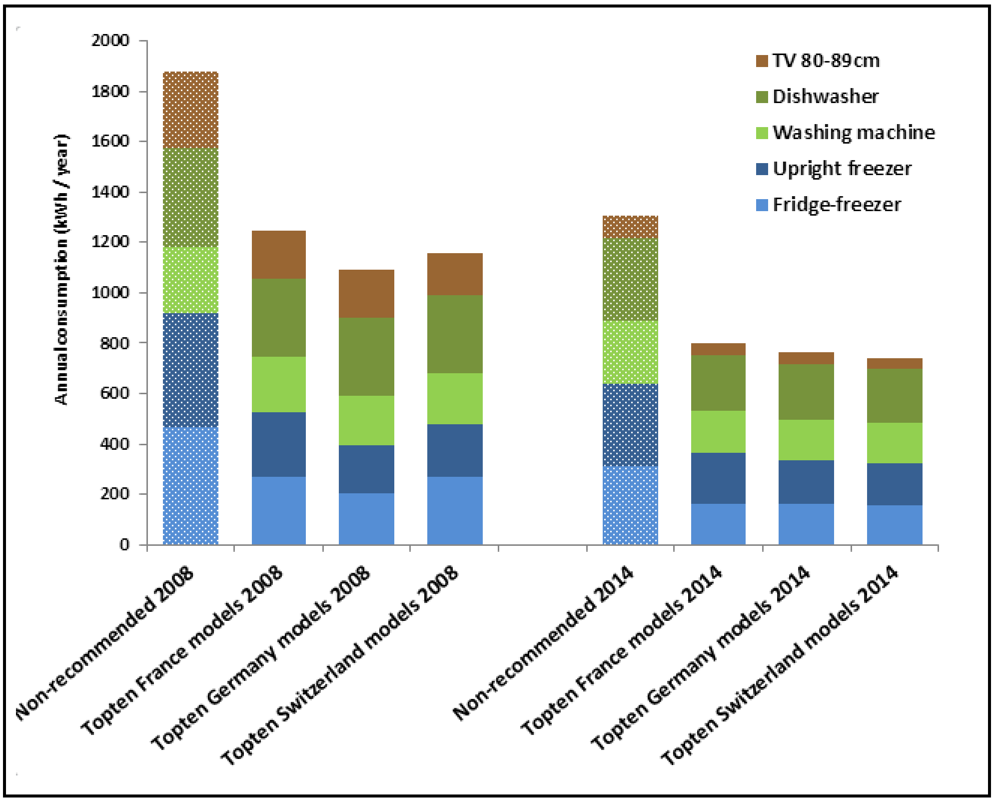


Figure 6: Average energy consumption levels for a household buying Topten-recommended products vs non-recommended ones in 2008 and 2014[3]

In 2008, buying Topten products resulted in a **34% to 42% saving** on energy consumption compared to the non-recommended products (the lowest value for France, the highest for Germany). Seven years after, despite a significant reduction in the consumption of the non-recommended models (some 30%) due to technological improvement and regulation, the savings in 2014 are still **38% to 43%** compared to the non-recommended (the lowest value for France, the highest for Switzerland).

In absolute terms, a French household buying average Topten products instead of non-recommended in 2008 would have saved € 92 per year on its energy bills. In 2014, the same process led to a similar saving of € 94 / year[4].

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[3] Note: for Germany, TV data was missing for 2008. We assumed the same level than in France.

[4] Calculations have been made using the Jan. 2008 electricity price for the 2008 figure and the Jan. 2014 price for 2014. Full prices for a 6 kVA power regulated tariff (source: Données Pégase).

Figure 6 also shows a higher similarity in Topten-recommended levels in the three countries in 2014 compared to 2008. This may be due to higher market integration, but also to more similar Topten criteria as new EU energy labels have provided the means for facilitating the definition of such criteria (e.g. new label class levels).

It is relevant to note that in total, the 2014 non-recommended level is not very far from the Topten-recommended levels of 2008 (only 12% higher on average), suggesting that a complete market upgrade in a seven-year timeframe is feasible and that good energy efficiency policy should aim for that. However, the 2008-2014 observation has a lot to do with the spectacular increase in TV efficiency and not just with Ecodesign policy decisions, as EU minimum energy performance requirements have been far from prescribing the level of the best of 2008 (see [5] for a detailed analysis of the regulatory levels in Ecodesign).

Affordability aspects

Although the previous parts have demonstrated that the top efficient segment of the market has made huge progress and is still bringing much benefit to consumers, a question remains about the affordability of the super-efficient products and their potential to become mainstream technologies for all.

A typical market rule is that more efficient products are placed on the market with a price premium (that lasts for some time until the technology eventually becomes mainstream). These premiums vary from product group to product group (they are more substantial in the appliance sector than in electronics), and have specific dynamics [7]. There is no doubt that whatever the year, buying Topten-recommended products instead of standard or low-end ones will typically be more expensive on average. In this paper, we are not making a full-market analysis, so we cannot compare the Topten levels to the rest of the market. However, what we can do is check if across the years Topten products have become more or less affordable than they used to be before.

Figure 7 shows the evolution of the average purchase price of Topten-recommended models for a basket of four products (fridge-freezers, upright freezers, washing machines, and dishwashers) from 2008 to 2014. (TVs have been left out because price trends in the 80-89 cm range are too uncharacteristic: as screen sizes increased steadily, 80-89 cm models have progressively turned from high-end to very standard products, and their prices have dramatically dropped between 2008 and 2014 irrespective of energy efficiency improvements).

<u>Note</u>: Figure 7 is based on average market prices collected by Topten guides at each selection update. Purchase prices can be very fluctuant, and statistics based on a small market segment should be taken with severe precautions. Discussions on detailed figures are irrelevant, and only very general trends may be looked at. This is why we are not indicating price values, but only annual evolutions using a base index 100 in 2008 for each country.

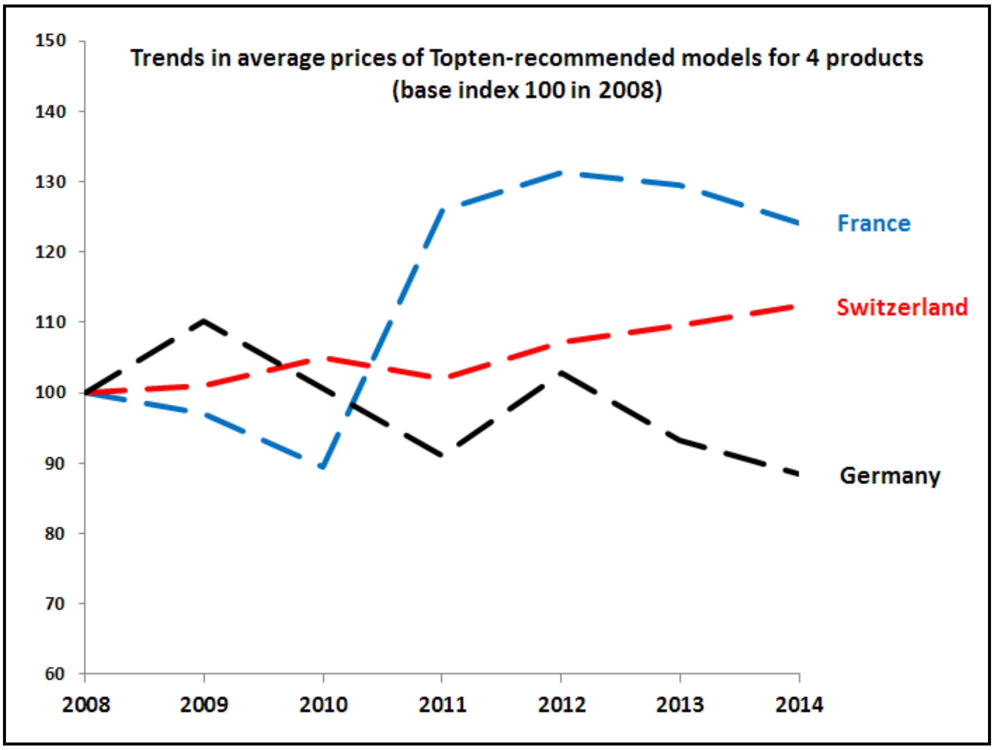

Figure 7: Average price evolution for a basket of Topten-recommended fridge-freezers, upright freezers, washing machines, and dishwashers

Figure 7 shows differentiated trends. While in France, the level of price premiums seems to have substantially increased around 2010-2011 (leading to 25% higher prices in 2014 compared to 2008), in Germany prices follow a downward trend with Topten-recommended models 10% cheaper now on average. Switzerland is in the middle. Several tentative explanations may be offered:

- First (as we have seen), the top of the market in 2008 in Germany was already more efficient than in France. The French market 'caught up' after 2008, leading to a more visible premium effect in the period 2008-2014.
- Second, the price of Topten appliances tended to be higher in absolute terms in Germany than in France before 2010. There has been a convergence trend, with prices becoming closer around 2011.
- Third, the trend in Germany may be explained by the fact that top-efficient products are more popular, more widespread, and have higher sales than in France, where they remain considered as high-end products. Market figures show that in the beginning of 2013, A+++ appliances represented 23% of the sales in Germany compared to only 5% in France [8].
- Last, small disparities in selection criteria may also have reinforced the contrast between trends. As an example, Topten France was recommending both A+ and A++ freezers until 2010; when the selections could then be restricted to A++ only, the A++ price premium effect materialised more visibly on the French curve. Switzerland and Germany had already been able to move to A++ only since 2008; their curves do not incorporate this effect in 2010.

All in all, the following (cautious) conclusions may be offered. On average, a Topten basket of the four products appeared even more affordable in Germany in 2014 than it used to be in 2008. In Switzerland, it cost about 10% more (a less than 2% per year increase). In France, consumers had to pay substantially more on average for top efficient appliances. However, this averaging can hide huge price variations within the same product category. For example, the prices of the Topten-recommended washing machines in France in 2014 ranged from € 500 to € 2000. French consumers should then be careful to choose wisely when they want to purchase efficient appliances.

In parallel, the average energy performance of Topten-recommended models strongly increased since 2008 as we have seen in the previous section. According to our calculations, the savings over the product lives in 2014 Topten products more than compensate the purchase price increases for Switzerland and even for France[5]. It means that in a total lifecycle cost perspective (including both the purchase price and energy/water running costs), Topten-recommended products in 2014 are on average more economical than in 2008 in all three countries.

Conclusions and recommendations

In this paper, we have presented some lessons learned from historical data gathered by Topten guides in France, Germany, and Switzerland between 2008 and 2014 for five product categories.

- We have identified a very substantial progress in the energy performance of the top products placed on the three markets over seven years (25% to 50% less energy consumption, even more for TVs). Best appliances are now largely exceeding the thresholds of the top EU energy labelling classes introduced in 2010. These labels appear to have been successful in stimulating a steep improvement until 2012, but trends look flatter now. This suggests a strong need for revising the labels, ensuring the scales are sufficiently ambitious, and estimating technological potentials more accurately.
- For a typical household, it still makes much sense in terms of energy conservation to purchase super-efficient products compared to low-end ones. In 2014, consumers could still achieve around 40% energy savings by choosing Topten models, a percentage similar to 2008. And this is true despite the fact that EU Ecodesign regulations and technological progress have substantially improved the bottom of the market. A remarkable observation is that the bottom of 2014 in our analysis is not far from the best Topten levels in 2008, suggesting a nearly full market upgrade over seven years (although the situation varies from product group to product group).
- As regards the affordability of top efficient products, the situation appears quite contrasted between the three countries. While in Germany Topten products seemed on average even more affordable in 2014 than in 2008, for France there has been a substantial increase in price premiums (25% overall for a basket of four white appliances). Switzerland lies in the middle. These observations are based on limited statistics and should be taken with precautions, however it would be interesting (if they are confirmed) to do further research to better identify the root causes of these differences. All in all, in a lifecycle cost perspective Topten-recommended products in 2014 are on average more economical than what they were in 2008, even for France. It is therefore important to reinforce consumer education on the lifecycle perspective.

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A prospective study of household refrigeration and washing appliance energy use in French households to 2030

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Abstract

This paper reports the findings of a study funded by ADEME to investigate the socio-technical factors likely to influence the energy consumption and savings opportunities for refrigerators, washing machines and dishwashers in French households to 2030. The scope involves an analysis of the technical opportunities to improve the energy efficiency of these appliances as measured under the existing test procedures; however, it also includes a review of how current test procedures could be improved to better reflect real usage characteristics and the additional opportunity for savings were this to occur. In addition, the study includes an assessment of the influence of the typical spread of user behaviour on the energy consumption of these products and thereby sheds light on the opportunities to reduce energy consumption through improved communication of savings opportunities to end-users.

Overall, the analysis indicates that limitations in current tests standards concerning a lack of flexibility regarding the temperature control of food storage requirements are leading to safe design options not being adopted that could reduce the actual energy consumption of cold appliances by about 45%. Furthermore, simulations show that it is possible for a typical refrigerator-freezer to attain an energy efficiency index of 50% lower than the current class A+++ limit and that the least life cycle costs should be around the A+++ level from a cost of production perspective. For washing machines and dishwashers it is also shown that attainment of EEI levels 50% better than the class A+++ limit is achievable.

The study projects the fleet average efficiency of EU appliances by 2030. Through the application of a set of sociological vignettes that describe and analyse a set of characteristic French families with regard to their use profiles for these major appliances, the influence of user behaviour on product energy consumption by product type is further assessed. On average it's projected that the average energy consumption for domestic refrigeration will fall by 73% from 2010 to 2030, and the average for clothes and dish washing will fall by 76%. Technological effects dominate but there is a significant additional potential to reduce consumption through behavioural optimisation. In 2010, the gap in per capita consumption between the lowest and the highest consuming households is a factor of 2.7. In 2030, under a conventional change scenario the difference is a factor of 3.8, but becomes a factor of 10.2 if optimal behaviour is adopted by one of the households.

Introduction

This paper presents the findings of a new study by ADEME to investigate the socio-technical factors likely to influence the energy consumption and savings opportunities for refrigerators, washing machines and dishwashers in French households to 2030 [1]. The objective of this study was to conduct an in-depth investigation of the two major electricity-specific domestic energy end-uses (cold appliances and washing appliances) via a socio-technical approach to examine potential trends in energy use to 2030. The approach required taking into account all elements of socio-technical systems, namely the technical characteristics of the equipment and its evolution, articulated with the different social and societal dimensions of fresh and frozen food, laundry and dishwashing. It also entailed consideration of emerging technologies which are associated with these services, such as innovative textiles and vacuum preservation.

From a methodological point of view, the work was organised in three phases:

1) The conduct of technical and sociological literature reviews on the relevant equipment. This comprised a sociological synthesis to help identify the main structural trends in lifestyles and the use of refrigeration and washing equipment that might be expected to evolve from now to 2030. A second bibliographical study focused on the technical aspects of cold and washing appliances. This was used to identify and assess all the relevant foreseeable technological options that could be deployed by 2030 and in particular to identify opportunities for energy saving technology but equally for new service features for the appliance types under consideration and to assess these from the point of view of: their maturity; the expected time horizons of their development, marketing and deployment; the potential technological obstacles to be overcome; and the emergence of market opportunities.

2) A socio-technical assessment of expected trends and developments to 2030, leading to the construction of a set of eight typical household situations in 2030 with respect to lifestyles, product ownership, services, features and usage. This is supported by an in depth technical analysis of the expected energy performance characteristics of cold and washing appliances in the same year.

3) Simulation of the expected energy consumption by these appliances in 2030 in each of the eight archetypical households identified and assessment of the range of expected outcomes as a function of sociological/behavioural and technical factors.

Step 2 required both an in-depth technical and economic analysis of the appliance types and their expected developments to 2030 and an equally in-depth socio-behavioural assessment of French households and their characteristics with respect to the ownership and operation of these products and the related services they provide. This analysis of "what households will be willing to do with these devices," assessed the structural elements of changing lifestyles. By 2030, the main trends in living conditions considered the demographic shift towards an aging of French population for whom maintenance at home for as long as possible is a driver, urbanisation and urban densification, with smaller households and associated changes in the housing stock, diversification of family forms and the broader development of intergenerational and other cohabitation practices. Greater sensitivity to energy and environmental issues are likely to go hand in hand with an increasing sophistication of domestic appliances to be "smarter", connected and communicating. The primacy of comfort, consumption yet also of energy saving as a social value should remain as a strong a group of trends as are those concerning standards of hygiene and cleanliness. In a context of a sustained economic crisis, the strengthening of the second hand appliances market is anticipated as is a strengthening tendency for consumers to be more proactive in seeking information about products and comparing the offers available to them. Eating behaviours are becoming more diverse with trends towards shopping and eating at a wider variety of food outlets, combined with a de-synchronization of traditional meal times and behaviours with individualised eating patterns. The trend toward an increasing proportion of meals to be in canteens, restaurants or from fast food outlets will most likely be accompanied on the one hand by increased consumption of pre-prepared meals and frozen foods, yet on the other hand, with the development of short-lived fresh produce potentially accompanied by a return of culinary preparations with new food preservation requirements. At present, cold appliances remain indispensable technical objects, constitutive of modern comfort. The degree to which consumers access information concerning their operation (regarding the positioning of the device, storage temperatures, optimal location of food, cleaning, etc.) is limited. Consumers have multi-faceted expectations regarding health (risk management), functionality (food preservation, reliability, silence, self-defrosting and self-cleaning, self-closing doors, etc.) and in terms of modularity with dedicated compartments providing different services. These expectations also encompass design, the choice of features (e.g. ice distribution, ice making, etc.) and ability to communicate with users (display screens) and network interconnectivity (home automation, automatic control, etc.). Washing devices also remain marked by many uncertainties regarding their use, including the extent to which the machine is fully loaded, and the choice and performance of the various programs (eco, normal, short, etc.).

Step 3) addressed the modelling and simulation of the appliance energy use as a function of all these parameters as captured through the earlier consideration of technological trends and the socio-technical trends assessed in Step 2.

Techno-economic opportunities to improve appliance efficiency

The techno-economic analysis conducted in the study (one aspect of step 2 above) set about identifying how the efficiency of domestic cold and washing appliances would be expected to improve from the current time to 2030. This entailed:

a) analysis of the historical rates of efficiency improvement in order to establish a techno-economic learning curve

b) identification and screening of promising technologies that could potentially be applied to save energy in future designs

c) a techno-economic analysis of the application of known higher efficiency design options to derive life cycle cost curves based on today's technologies and costs

d) adjustment of the results for step c) in the light of those from step b) and reconciliation of all the findings to produce a common estimation of how product efficiency is likely to evolve over the period to 2030.

As public policy and especially Ecodesign and energy labelling regulations are such an important driver of efficiency for these products step d) also entailed consideration of how such regulations were likely to evolve over the intervening period and how they are set to influence average product efficiency.

The above analyses were conducted under the presumption that there is no significant change in the test procedures used to define product efficiency; however, an additional analysis was conducted to determine whether there was much potential for additional energy savings through an evolution towards more intelligent test procedures that better reflect real world energy usage and hence fully reward all design options that can save energy in real use.

Current trends and learning curves

Cold appliances

For cold appliances it was found that the average rate of change in the average energy efficiency index for new appliances sold from 1992 to 2013 had been -4.6% per year. Despite several revisions of both energy labelling and MEPS regimes the observed rate of improvement remained relatively stable over this time frame. If this rate of improvement were to continue until 2030 the market average EEI would decline from 39.8 in 2013 to 17.6 in 2030 i.e. to some 20% below the current A+++ threshold.

Washing appliances

In the case of washing machines the rate of change in the average energy efficiency index for new appliances sold from 1992 to 2013 had been -3.2% per year. While for dishwashers it was -1.9%/year. If these trends were to continue until 2030 the average EEI for washing machines would decline from 56 in 2013 to 31.8 in 2030, while for dishwashers it would decline from 63 in 2013 to 45.5 in 2030. These are respectively 31% and 9% below the current A+++ threshold.

Lifecycle cost analysis using a design simulation tool

Life cycle cost analyses were conducted for typical refrigerator-freezer models to determine the potential for efficiency gains and their implications on product costs (the purchase price and operating costs). A simpler analysis was conducted for washing appliances.

Cold appliances

A variety of potentially higher efficiency design options were considered for cold appliances including:

- thicker/higher quality foam insulation
- vacuum insulation panels

- brushless DC fans for the evaporator and condenser
- forced convection condensers
- larger/higher capacity evaporators and condensers
- flow-optimised natural convective cooling
- optimised capillary tubes
- higher efficiency fixed-speed compressors
- variable speed/capacity compressors
- adaptive defrost (i.e. intelligent control of the defrost heating system)
- strengthened controls with intelligent control algorithms
- dual-loop cooling circuits i.e. one for the fresh food compartment and one for the frozen food compartment
- electrostatic valves
- alternative refrigerants with lower global warming potential

Most of these are already deployed in some proportion of cold appliance designs but potential savings remain from their more systematic deployment. The effect of applying these designs on the EEI of a typical refrigerator-freezer was simulated using a set of dedicated refrigerator energy analysis software tools. The results show the impacts of successive design changes on energy performance wherein an energy class B product is progressively improved and passes beyond a typical current product (the fourth option having an EEI of 38.1) to pass beyond a class A+++ (EEI<22) and ultimately attain an EEI level of roughly 50% lower than an A+++ (Table 1).

Table 1. Impact of technology changes in the energy performance and life cycle costs of a typical refrigerator-freezer

	Energy consumption	**Reduction in energy from previous design option**	**Improvement % from previous design option**	**Purchase price**	**Delta in purchase price**	**Life cycle cost**	**Payback period**	**EEI**
Technical option	(kWh/yr)	(kWh/yr)	(%)	(Euro)	(Euro)	(Euro)	(year)	%
Base case model	412	0	0%	659	0	1130	-	69.2
Improvement of the evaporators	391	21	3%	667	8	1114	3,3	65.7
Optimisation of the evaporators	332	59	8%	671	12	1050	1,3	55.8
Insolation thickness of 40mm for the fresh food compartment and 50mm for the freezer compartment and compressor niche	227	105	14%	674	15	933	0,7	38.1
Replacement of compressor by high efficiency compressor	127	100	14%	782	123	927	3,9	21.3
Insolation thickness of 50mm for the fresh food compartment and 75/80mm for the freezer compartment and compressor niche	102	24	3%	786	127	903	3,7	17.2
Maximum use of vacuum insolation panels	67	35	5%	1228	569	1305	15,0	11.2

Source: Simulation analysis conducted for the study presented in this paper

The findings show that the life cycle cost is minimised for the product with an EEI of 17.2, which is 22% below the current A+++ EEI threshold. The analysis of the purchase price is based on the estimated cost of production to which a constant mark-up percentage is applied that takes account of producer and supply chain profit margins and costs. In practice current average purchase price differentials may be somewhat higher for A+++ products but the present analysis suggests this phenomenon is related to the correlation with high efficiency of other product quality, brand and pricing factor elements and is not a simple reflection of the incremental cost of producing higher efficiency products.

Interestingly, the current least life cycle cost EEI level of 17.2 is very close to what the learning curve analysis suggests would be the market average level in 2030 (an EEI of 17.6). This analysis demonstrates that the learning curve projection is both fully plausible and reasonable.

Of all the alternative technologies considered the most promising that is not reflected in these analyses is magnetic refrigeration. A number of exciting developments are reported in the literature for this technology and it seems quite plausible that it may become viable for domestic refrigeration over the coming decade. Were this to be the case it is possible that a faster and deeper rate of improvement in the EEI could occur perhaps leading to a reduction in the market average EEI to 14 by 2030 (in place of 17.2 without such developments).

Washing appliances

In the case of washing appliances the findings of the learning curve projections was complemented by consideration of what is currently known about the potential to apply new or higher efficiency technologies to attain lower EEI levels. This combined a literature survey, with informal expert interviews and an analysis of the current best available technologies.

In general, the performance of a washing machine is the result of four factors: temperature, the duration of the wash cycle, mechanical agitation and detergents. The detergent is specified by the test standard while there appears to be limited scope to further optimise performance through more efficient mechanical action. In current machines the main opportunity to improve the EEI is related to optimising the wash temperature and length of the wash cycle. Other options (among those which are not yet already fully deployed) include [2]:

- The use of high efficiency motors (such as "inverters" and permanent magnet motors).
- The use of load sensing devices and controls that adapt the program to different loads.

An assessment of the best available technology at the time of the analysis found that the Electrolux WA SL6 E had an EEI of 31.9, which is 31% below the minimum threshold of A+++ (EEI<46). With a capacity of 9 kg, it consumes 152 kWh/year for 220 cycles per year (with weighted cycles according to the test standard). Its' energy consumption per wash cycle is 0.9 kWh for a full load 60°C cycle, 0.58 kWh for a half load 60°C cycle and 0.46 kWh for a half load 40°C. However, even more significant energy savings can be produced using heat pump technology and at least one model on the market now uses this to attain an even lower EEI. The 8 kg V-ZUG Adora SLQ WP has an EEI of 22.8. It consumes only 98 kWh/year for 220 cycles weighted according to the test standard and uses 9880 litres of water. Although this product has an EEI of less than 50% of the A+++ limit the price at the time of the analysis was far above a level which could render the machine economically viable to an end-user from a lifecycle cost perspective.

In the case of dishwashers, the most efficient machine in the CECED database considered in the Ecodesign Omnibus study [2] was reported to have an EEI of 41, which is 18% more efficient than the minimum required for a machine A +++ (EEI<50). This machine uses 1960 litres of water per year (7 litres/cycle and 280 cycles per year) and has 13 place settings. The purchase price of this machine is around 1500 euros. It uses zeolite drying technology and has a cycle time of 195 minutes. The annual energy consumption is 194 kWh (about 0.69 kWh / cycle). However, just as was the case for washing machines the highest efficiency dishwasher found on the market also uses a heat pump. The V-ZUG WP Adora SL has an EEI of 29.7 i.e. some 40% lower than the A+++ threshold. However, this product was priced at about three times the typical price of a dishwasher and so would not be cost-effective for an average European consumer without a substantial price reduction. A simple theoretical analysis indicates this may not be the case even were heat pump technology to become the norm. For example, were the use of a heat pump to reduce an A+++ products energy consumption by 30% and cost no more than €150 above the price of a typical A+++ product it would imply a simple payback period of 40 years at the typical electricity tariffs and usage levels seen in France.

Considering these factors a continuation in the historic learning curve for the EEI was considered the most plausible default scenario to 2030 for both dishwashers and washing machines, while not discounting the possibility for new, so called disruptive, technologies to be developed which could change this perspective. This is predicated on a regular renewal of the Ecodesign and energy labelling regulations to reflect the on-going techno-economic developments and savings potentials.

The impact of test procedures

The previous analyses all assumed that the energy performance test procedures remain invariate, while the lifecycle cost analyses assume that the test procedures are representative of actual product use. In reality though there are several reasons to question this assumption and this has a bearing on the potential for real energy savings.

Cold appliances

Adoption of IEC 62552-3

The current standard EN 62552:2013 measures energy performance for a single ambient temperature of 25°C and hence manufacturers optimise their product performance to this condition. The new international IEC 62552-3:2015 test standard requires testing at two ambient temperatures (16°C and 32°C). Interpolation can then be used to derive the expected energy consumption at 25°C i.e. as is currently required under EN 62552: 2013 and for the derivation of the EEI. In principle the use of two ambient temperatures with interpolation in between will prevent products being optimised to a single ambient temperature. This should produce more realistic (representative) energy performance results and lead to real energy savings as actual kitchen temperatures will fall well below 25°C in the winter at night time (when the space heating is set back) and can have significantly higher temperatures in the summer peak, especially when cooking appliances are also operating.

To see the potential impact of this change in standard nominal consumption of a typical refrigerator-freezer, energy performance simulations were conducted using a cold appliance energy simulation tool. The results show an increase in the nominal (interpolated) energy consumption of up to 25% due to the tendency of products with a fresh and frozen food compartment not to perform equally well at higher and lower ambient temperatures. It should be appreciated that this is simply the nominal energy consumption of the same cold appliance when simulated at 25°C and then when simulated at 16°C and 32°C and interpolated to 25°C. Thus ironically while switching to the IEC standard could increase nominal energy consumption it would most likely lead to a reduction in actual energy consumption because it would encourage adoption of robust design solutions, which are under rewarded with the existing test procedure. The impact of this effect is estimated to lead to a future energy saving of ~10% after the influence of the hypothetical change in the standard has had enough time to be reflected in product design changes.

Impact of improving freezer temperature control

End-use metering studies have found that a substantial proportion of freezer compartments operate at a much lower temperature than the recommended -18°C[1]. This leads to a considerable waste of energy yet measures which might reduce this wastage are not rewarded in the way that the energy performance is currently measured and the EEI is determined. For example, a simple solution would be to reward products that provide a warning alert when the freezer is operated below recommended temperature levels for any significant period of time. Or to reward appliances that automatically return the storage temperature to the recommended level after a period of time without further manual

[1] The temperature test in the current EN 62552: 2013 standard requires three and four star freezer compartments to be maintained at a maximum test package temperature of -18°C. The ECUEL end-use metering study conducted in 100 French households in 1999 first demonstrated the magnitude of the energy wasted due to overly low freezer thermostat settings.

override. Simulations conducted for this study based on data of the typical distribution of thermostat set points suggest that ~26% of energy is wasted by this effect and it is conservatively estimated that half of this (i.e. ~13%) could be saved by measures that encourage producers to install features that will reduce the risk of consumers operating products at below recommended temperatures for long periods.

It is also important to comprehend the basis of the choice of -18°C as the recommended frozen food storage temperature and its implications for real energy use. Bacteria will no longer propagate at temperatures inferior to -10°C and it is perfectly possible to have excellent food preservation if food is chilled quickly when first introduced into a freezer compartment by operating at -18°C and then the storage temperature is allowed to rise to a higher temperature (say -15°C) if no new food is introduced. Sensor technology is now perfectly capable of detecting when foodstuffs have been introduced into a freezer (as opposed to the door being opened) and thus to apply a dynamic temperature control in response to real use (i.e. drop the temperature to freeze relatively quickly when new products are introduced and then let the temperature drift up to a slightly higher storage temperature once they have been frozen). Simulations conducted for this study show that allowing such a dynamic freezer temperature (between -18°C and -15°C) would save ~30% for a typical refrigerator freezer. The current static storage temperature requirements would have been appropriate in an earlier era when it was difficult to control the storage temperature using analogue controls but in the current digital era this would appear to be a missed opportunity to save energy for no inconvenience to the end user.

Summary of test procedure improvement potential

Were all the changes alluded to above to be adopted i.e. a switch to testing at two ambient temperatures with interpolation to 25°C, encouragement of designs that alert consumers to overly low freezer thermostat settings and a switch to dynamic control of the freezer temperature that allows normal storage at -15°C, then collectively it is estimated that there is a 45% real energy consumption savings potential compared to continuing with the existing cold appliance test procedure. These savings potentials are not reflected in the current EEI calculation and hence would require both modification of the test procedures and the manner in which the EEI is defined to be captured.

Washing appliances

Dishwashers

When determining dishwasher energy performance for appliance labelling or MEPS suppliers use the eco program or another energy efficient wash cycle; however, in practice consumers use a variety of programs during their everyday operation of a dishwasher. As these programs are not considered in the derivation of the EEI there is little incentive for producers to optimise their energy performance and it is likely that many of these additional programs will use more energy than the program used for labelling purposes. For example, the temperature of the normal or automatic program is often between 60 and 65°C, while that of the eco program is usually 50°C; however, the last Eco-design preparatory study reported that the "normal" program is the most commonly used. In principle, there would be an incentive for all programs to be more efficient if a mix of cycles was taken into account in the calculation of the IEE. This was not adopted in the latest version of the European test procedure (EN 60436:2008+A11:2012, EN 50242:2008) but should be considered in future revisions.

Washing machines

The energy performance test for washing machines (EN 60456-2011) already requires the use of a basket of programs as the reported energy consumption is the average energy consumption of seven test cycles (3 standard cotton cycles at 60°C, 2 half-load cotton cycles at 60°C and 2 half-load cotton cycles at 40°C). In practice though there is still a disparity between this choice of programs and real user behaviour. In general studies have shown that typical European consumers use fewer wash cycles per year than is assumed in the energy label energy calculation, use lower temperatures and do not always use the cotton program [2]. A bigger issue may be caused by the fact that there are currently no constraints on the permitted wash time for program cycles used to determine the EEI. According to research reported in [2] by Stiftung Warentest in Germany, which tested washing machines using cotton programs at 60°C, some machines actually wash at temperatures of 45-50°C. This saves a lot of energy; however, the reduced temperatures are compensated by a cycle that lasts longer, so while the “normal” 60°C cotton program typically lasts between 2 and 3 hours, the "Eco 60°C" program typically runs for 3-5 hours. Given the loss of convenience longer wash cycles will cause it is quite likely this development will lead to a greater proportion of consumers ignoring the eco program and opting for the normal program. Unless addressed in the future this practice risks there being a growing disconnect between the actual energy usage and the nominal energy usage. Furthermore, as the shorter wash programs do not have to be used in the EEI determination it is quite likely there will be a growing disconnect between the nominal EEI ranking and the actual (in use) appliance energy efficiency performance, which would weaken the real benefit of the energy label and Ecodesign regulations.

Sociological analysis and its impacts on the projected demand

The sociological analysis focused on the development of a set of eight archetypal household “vignettes” that could be imagined to represent certain strata of the French population in 2030. This approach aims to go beyond the information provided by conventional modelling tools that are only geared toward the representation of technical parameters (e.g. dimensions, walls, cooling and insulation technologies etc.) and do not allow user behaviour to be considered separately. The method of estimating energy consumption included in the study aims to integrate the characteristic spread in the conditions of use of the appliances. It is therefore essential to provide specifics on actual situations, the effects of purchasing choices and usage behaviours.

The sample of eight households is based on the major trends of population and lifestyles, as well as the prospects of technical and regulatory developments in 2030. It shows a diversity of household profiles, practices and diverse lifestyles, which are not representative of the general population, but are significant and can describe prospective situations expressing the diversity of situations. The cases considered do not include the wealthiest households or the poorest households, which have specific issues and behaviours.

The identification and selection of family archetypes

Traditional approaches regarding long-term projections of energy demand in domestic appliances are mostly based on the evolution of technical parameters with little or no accounting for changes in consumer behaviour. When such changes are a component of demand modelling, it is often in the form of considering marginal changes in the average size or load of appliances. The reason for such a representation of behavioural variants is that there are virtually no methodological means to measure, project and describe the evolution of contrasted behaviours at the scale of thousands or millions of households.

The present study aimed to address this deficiency by projecting and modelling the combined effects of sociological trends and technological progress through conceiving 8 hypothetical “virtual” households living in the France of 2030. Each household is conceived to be an archetype of a common set of social and technical characteristics. Although no attempt is made to try to project the proportion that each of these household archetypes would be likely to represent in the overall French population in 2030, we assume, based on a careful examination of social trends, that each household could very well exist and be representative of larger parts of the population, hence their “archetype” status. The key idea behind such a construction is to highlight the potential diversity of consumer behaviours and to explore its potential impact on appliance energy use.

The structure of the sample of 8 families is oriented by the general demographic and economic trends at the national level. For instance, ageing households, smaller households, the rural vs. urban split are among the key demographic characteristics of the sample. However, there is no specific proportionality of the sample compared to national projections: we assume some of the 8 archetypes would be more common than others, while still allowing for a wide variety of behaviour to be described.

More specifically, each virtual household is organised around an integrated narrative that includes its: composition (adults and children), its revenue, type of habitat (size of house or apartment), choice of technologies and appliances, clothing and alimentation habits, and awareness of environmental issues. A lot of focus was dedicated to the internal coherence of each household, so that they would appear as much as possible as “normal” rather than “ideal” or “exemplary”. To enhance this approach, the team who elaborated the narratives used custom first names to refer to each member of the family and described their lifestyle as closely as they would for an actual family. Furthermore, the present study was conducted so as to be consistent with a long-term cross-sectorial national energy scenario published by ADEME in 2014 [3], so household characteristics remained in line with the general trends assumed in that scenario. A description of each family archetype is given in Appendix A.

For each household, three situations were considered:

- A typical situation for the specified archetype household in 2010
- An equivalent household in 2030, having the same composition and age categories, with the same behavioural characteristics with respect to cold and washing appliances, but applied to the new appliances they would be expected to be using in 2030 derived from corresponding projections in the evolution of regulations and technology to 2030
- An equivalent household in 2030, having the same composition and age categories, but with new behaviours that reflect the trends currently observed and characterised by the sociological component of the study.

Summary of assumptions on family behaviour with respect to cold and washing appliances

Each household's general narrative helped us to specify their behaviour with respect to cold and washing appliances.

First of all, we describe which appliances are present in the household, and characterise the size and nominal energy efficiency of the appliance. Energy efficiencies were derived from a study [4] for ADEME by Energies Demain and the CREDOC institute that projected sales and stock breakdown by energy label (from G to A6+, i.e. in an extended scale to represent technological improvements beyond today's scale which ends at A+++[2]). We defined an index of relative energy efficiency of the appliance corresponding to its position in the sales range for that year (for example, a relative energy efficiency of 5 means the appliance was in the top 20% of all sales in that year, whether that was an A++ in 2012 or would be an A5+ in 2025), Table 2. The trends in expected energy performance were informed by the techno-economic and learning curve analyses previously presented.

Table 2. Composition of three technological and behaviour situations for the same household

<table>
<tr><td colspan="3">Example of household no.2
A couple of 50+ middle class living in a suburban house, 15min. to the city centre.</td></tr>
<tr><td>Situations</td><td>Technology</td><td>Lifestyle & behaviour</td></tr>
<tr><td>Situation in 2010</td><td>1994 D class refrigerator of 350L (relative energy efficiency index at the time of acquisition: 3/5)</td><td rowspan="2">In this family, children have recently departed from home (for example, having completed their studies). This leaves the couple with significantly oversized appliances</td></tr>
<tr><td>Situation in 2030 with new appliances</td><td>2024 A+ class refrigerator of 350L
(same capacity & relative energy efficiency index at the time of acquisition)</td></tr>
<tr><td>Situation in 2030 with new appliances & lifestyles</td><td>2025 A4+ class refrigerator of 250L
(different relative energy efficiency index, different time of acquisition)</td><td>As smaller households become more common, it is easier for a couple such as this one to resell and adapt after the family got smaller. Relatively to their 2010 counterparts, they rely on a smaller refrigerator which is also more energy efficient.</td></tr>
</table>

[2] Note this does not imply any belief or support for the idea that more plusses should be used on future energy labels but is rather a convenient construct to indicate how many extra higher efficiency label classes were considered to be likely to be introduced by 2030 assuming equal efficiency increments.

Then, a series of hypothesis are created to represent the behaviour of the different members of the household. For cold appliances, behavioural characteristics include food consumption habits (for example, the amount and type of food brought to the refrigerator or freezer from different sources), the preference of the household for ready-made or self-preparation of their meals, and the frequency of refrigerator door openings. For washing appliances, behavioural characteristics include the number of cycles launched per week or per year, differentiating between water temperature and length of the cycle. The number of cycles is itself a function of the number of people in the household, typical clothing habits (sorting of same colours, delicate to wash) and the average load of the machine. In some households, washing habits vary across the members of the family, taking into account varying level of proficiency regarding the appliance and its use.

Summary of how the impact of user behaviour on appliance energy consumption was modelled

The impacts of technology and behaviour are modelled following a two-tier process:

The first tier of the process is based on the energy label of the appliance. Sales breakdowns by energy label class were derived from projections made by Energies Demain and CREDOC for ADEME [4]. Each energy label class (from G to A6+) is linked to a range of energy efficiency index (EEI), of which we took the average value as the EEI of the appliance. For example, a refrigerator of A3+ corresponds to an EEI between 18 and 22, resulting in an average EEI of 20. The EEI allowed us to define the energy consumption of the appliance under the usage conditions assumed in the test standard.

The second tier of the modelling process accounts for the variation between standard use conditions and the actual behavioural characteristics of the household. For cold appliances, we compiled results from existing literature on the impacts of use conditions on energy consumption. Most notably this relied on the work of Geppert [5]. This work aimed to quantify the impact of various real-use condition variables such as external temperature, number of door openings, introduction of foodstuffs at various temperatures, etc., Table 3.

Table 3. Example of simplified behaviour modelling relative to standard conditions of use

Modelled impacts of behaviour relative to the standard consumption of a 265L B class refrigerator (EEI 65) Base consumption 357kWh per year.	
Food load	+100Wh per water litre at 25°C
Door opening	+10Wh per door opening
Change in internal temperature (above or below 5°C)	-5% total consumption per °C above +6.5% total consumption per °C below
Change in external temperature (above or below 25°C)	10°C (ex: cave environment) leads to -40% total consumption 20°C leads to -20% total consumption Regular exposure above 25°C leads to +30 to +40% total consumption

For washing appliances, we modelled 8 typical wash cycles, from standard 40° cycles to eco 30° and 20° cycles. The amount of water to heat and the length of the cycle are the two main components of energy consumption in our model. This allowed us to set a ratio of consumption relative to the EEI consumption for each washing machine in our sample. A similar approach was extended for the dishwashers.

By comparing the energy consumption with or without behavioural inputs, we observed variations ranging from -5% to +95% consumption compared to standard-use conditions for cold appliances, and -70% to +115% consumption for washing appliances. The reason why the total energy consumption variation is larger with washing appliances appears to be that the number of people in the household is a stronger determinant of energy consumption for washing than for cold appliances.

On average across the eight households it's projected that the average energy consumption for domestic refrigeration will fall by 73% from 2010 to 2030, and the average for clothes and dish washing will fall by 76%, Table 4. Mostly this is due to technological effects which on average account for 95% of the expected reduction in energy consumption for cold appliances and 92% for washing appliances. However, while technological effects dominate the average expected changes there is a significant additional potential to reduce energy consumption through behavioural optimisation. In 2010, the gap in per capita consumption between the lowest and the highest consuming households is a factor of 2.7. In 2030, under a conventional change scenario the difference is a factor of 3.8, but becomes a factor of 10.2 if optimal behaviour is adopted by one of the households.

Table 4. Results from the simulation of appliance energy use in 8 French households in 2010 and 2030

Household no	1	2	3	4	5	6	7	8
No. of Adults	2	2	2	2	5	1	2	1
Age of adults	30	50	30+	65+	80+	35	80+	30
Revenue	+	+	+	++	+	++	-	-
Children	2	0	4	0	0	0	0	1
Energy consumption in 2010, kWh/year per appliance								
Refrigerator	137	283	88	239	362	280	261	387
Freezer	90	201	27	174	0	0	0	0
Cold	**227**	**484**	**115**	**413**	**362**	**280**	**261**	**387**
Washing machine	126	144	69	100	95	130	145	64
Dishwasher	134	80	83	87	34	124	0	0
Washing	**260**	**225**	**151**	**186**	**130**	**254**	**145**	**64**
Total	**487**	**709**	**266**	**599**	**491**	**534**	**407**	**452**
Energy consumption in 2030 with technological and behavioural changes, kWh/year per appliance								
Refrigerator	40	51	40	86	133	51	16	82
Freezer	50	0	6	74	0	0	0	0
Cold	**90**	**51**	**47**	**160**	**133**	**51**	**16**	**82**
Washing machine	15	15	26	38	15	11	8	13
Dishwasher	23	23	35	37	19	63	0	0
Washing	**37**	**38**	**61**	**75**	**35**	**74**	**8**	**13**
Total	**127**	**90**	**107**	**235**	**168**	**125**	**23**	**96**
Breakdown of technological & lifestyle change contributions to the evolution of appliance energy consumption from 2010-2030								
Cold	**-60%**	**-89%**	**-59%**	**-61%**	**-63%**	**-82%**	**-94%**	**-79%**
Technological	-69%	-65%	-76%	-64%	-66%	-82%	-68%	-68%
Lifestyle	8%	-24%	17%	3%	2%	0%	-26%	-11%
Washing	**-86%**	**-83%**	**-60%**	**-60%**	**-73%**	**-71%**	**-95%**	**-79%**
Technological	-58%	-58%	-72%	-67%	-58%	-82%	-68%	-76%
Lifestyle	-28%	-25%	13%	7%	-15%	11%	-27%	-3%
Total	**-74%**	**-87%**	**-60%**	**-61%**	**-66%**	**-77%**	**-94%**	**-79%**
Technological	-63%	-63%	-74%	-65%	-64%	-82%	-68%	-69%
Lifestyle	-11%	-24%	14%	4%	-2%	5%	-26%	-10%

As the sample of archetypical households is made-up of a set of very different household situations, the analysis has to focus on the two contradictory factors at play in the 2010-2030 timeframe concerning variations of both technology and lifestyles:

- On one hand, the individualization of lifestyles, whether in the form of fewer people per household or in the coexistence of several appliances for each member of the household, is a factor that acts to increase energy consumption in 2030 compared to the 2010 situation

- On the other hand, adjusting appliance size and capacity according to the needs of the household, sharing equipment between households and a growing attention towards saving money and energy are optimisation factors that act to decrease the overall energy consumption.

The variations in the archetypes also allows an examination of the potential for direct "rebound" effects to occur. This effect usually occurs when households that have limited their use of a particular appliance due to financial constraints switch to more efficient equipment. The avoided expenditure allows them to increase their use and/or product capacity in response to the savings made possible by the higher efficiency product. Although some households were projected to have a small increase in their energy consumption compared with what would have been expected through technological evolution alone, we did not identify, in the narratives, any situation where long-term technological gains were significantly offset by an increase of use. The main reason for this appears to be that households cannot increase their use of the appliances unlimitedly without breaking the coherence of the narrative. For example, there is a practical limit in the number of washing machine cycles a one-person household will do per week, independently of the appliance's efficiency. This is likely to be a reflection of a relatively saturated appliance market and, of course, does not consider potential in-direct rebound effects where the avoided expenditure is used for different types of goods and services.

Summary of results and conclusions

Comparing similar lifestyle situations between 2010 and 2030 but taking into account technological evolution, we observe an average 65% decline in energy consumption across all 8 households of the sample. This technological component in the 2010-2030 variation is the most important, representing the effect of technological progress driven by energy efficiency regulations over the composition of the stock of appliances. By adding the layer of behavioural changes derived from the household narratives and the main sociological trends at work in France between 2010 and 2030, we identify an average 10% supplementary energy consumption decrease. Furthermore, while typical inter-family behavioural variations projected for 2030 are expected to produce a variation of a factor of 3.8 in appliance energy use this could be much greater were some to adopt very low energy lifestyles and very high efficiency product choices.

The analysis also shows how important test procedure design can be in driving real energy savings. If the test procedures and energy efficiency indices don't capture the impact of key behavioural or operational energy savings opportunities then products are unlikely to be offered that will take advantage of these opportunities. In the case of refrigerator-freezers potential changes in the test procedure and EEI formulation have been identified that could increase actual energy use by ~45% were they to be adopted. In the case of dishwashers and washing machines limitations in the test procedures and EEI are identified that are likely to be causing nominal reductions in EEI to be occurring at a more rapid rate than are real energy usage.

By combining a simplified model of technology and behaviour with a more general narrative of lifestyle trends in France, our study highlighted the variety of situations that can co-exist behind traditional averaging. Using a sample of households instead of aggregated populations allows for a case by case analysis of how each parameter can evolve, and helps to identify incoherent or contradictory anticipations of future developments.

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Appendix A. Description of the sample of households considered in the analysis

	Summary	Key characteristics
1	High food autonomy & storage	Two adults and two children, living in a rural environment. One of the adults is a farmer, in 2030 the farm has converted to organic modes of production; Compared to 2010, the family is more self-sufficient in terms of food, with an increased need for refrigerated food storage. A second freezer is installed in the house, resulting in larger energy consumption than what technological improvement would have secured in a baseline scenario.
2	Appliances with adequate capacity	Two adults living in an urban environment in a middle-sized French city. In this family, children have recently departed from home (for example, having completed their studies). This leaves the adults with significantly oversized appliances. In 2030, a gain of 50% relative to the baseline scenario is achieved by switching to smaller, more adapted appliances regarding the household new situation and composition.
3	Individualised lifestyles	Two adults and four children in a large suburban house. In this family, there is a growing tendency for each individual to organise his or her life independently from the others. Meals are taken separately and at different times of the day, older children wash their clothes themselves, etc. Compared to a baseline scenario, this new lifestyle amounts to an increase of about 50% of the total energy consumption of the four observed appliances. However, this result is still less than 30% of the 2010 initial consumption, largely because of the improvement in technological efficiency.
4	High revenues, extra functions	Two adults, retired with high revenues. This case considers the effects of combined high revenues and the pursuit of a high standard of living. This household goes for recent, state-of-the-art but also over-equipped appliances, with a profusion of extra functions such as wine cellar or ice dispenser. The final rise in consumption is moderate, about +10% compared to a baseline scenario with no evolution in lifestyles.

5	Five-person house-sharing	This household illustrates the case of a home shared between five elderly people. In the 2010 version of this case, each person lives in his or her own house. In the 2030 version, they share a common house, with some appliances in common. This is envisioned both as a way to achieve more energy efficiency but also as a solution to the growing problem of isolation and social exclusion of elderly people. Compared to its 2010 equivalent, the new lifestyle is much more efficient (drop in 75% of final energy consumption).
6	Smart, connected appliances	This household is composed of one single person (young adult). Technologic capabilities of the appliances are pushed to the maximum. In this household, appliances are “smart”, “connected” and they share information with the owner via his phone. This domestic network helps to plan daily actions in more efficient ways, for example, the fridge keeps track of the food inside, suggests meals and recipes to avoid unnecessary waste, etc. This efficiency is somewhat mitigated by the rise of all-year-round standby consumption because appliances are always activated to participate in the network.
7	Best appliances, rebound effect	Two retired elderly people, living in a deep rural environment, limited budget. This case illustrates the situation of many households for which the electricity bill is high, but where there is no extra cash to allow investing in better equipment. This results in a permanent constraint on how often the appliances are used. In the 2030 version, we suggest that support programs, for example including the leasing of state-of-the-art equipment, can help the household to move away from a constrained lifestyle. Because better appliances have a lighter energy footprint, they can be used more frequently. This “rebound” effect does not compensate the efficiency of switching to better equipment.
8	Exchange of services between families	This one-parent family (one adult, on child) faces financial constraints by developing a network of social interactions, where neighbours and friends contribute by exchanging skills and services. This alternative lifestyle goes beyond the simple sharing of appliances between families. As food is prepared and clothes washed together with other households, it challenges the very definition of individual or collective lifestyle.

Projections of long-term household electricity use in Germany - behavioural aspects, investment decisions and discount rates

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Abstract

The evaluation of the impact of energy efficiency policy on energy demand requires estimating both technological as well as behavioural aspects. Typically, energy demand models represent behavioural aspects and non-monetary barriers through high subjective discount rates applied to investment decisions. This approach has led to a considerable amount of confusion and an extensive and controversial discussion following the impact assessment of the 2020 energy efficiency target. Especially for residential energy use, where purchase decisions are typically strongly driven by preferences and subjective risk perceptions, and where a number of studies have shown that information based policy measures such as Energy Labelling increase the willingness to pay for high-efficiency appliances, it is essential to take empirical findings and policy impacts into account when specifying discount rates. Our study presents a detailed investigation of the role of discount rates for projecting the residential electricity demand in Germany until 2030, considering the currently implemented policy measures. Our model is based on a discrete choice approach that allows for controlling the sensitivity of consumers to the total cost of ownership as well as their sensitivity to purchase prices. We review empirical studies that investigate the effect of energy efficiency policy on consumer decision making and discount rates and link the findings to energy demand modelling. The literature review suggests that it is crucial to use different discount rates for different technologies and by running sensitivity analyses, our study shows that it is essential to dynamically adapt the discount rates as policy measures that affect investment decisions are implemented. We conclude that tools for policy evaluation need to increase their level of detail taking into account individual technologies and provide an increased level of transparency regarding discount rates.

Introduction

Improving energy efficiency can significantly contribute to climate change mitigation and deliver a range of benefits to the economy and society [1]–[3]. Besides being one of the main pillars of European climate and energy policy [4], energy efficiency can lead to significant benefits at an individual, sectoral and macroeconomic level.

The residential sector, which accounts for more than a quarter of final energy demand in the EU, has been found to offer a large and cost-effective energy efficiency potential, in particular for renovating existing buildings and purchasing new household appliances [5]–[7].

Policy measures that address household investment decisions play a key role in the diffusion of energy efficient technologies and practices. A key question is to what extent policy measures can guide consumers' investment-decisions towards more efficient choices. This is especially challenging in the European context, as the various countries differ widely in many aspects including their socio-economic background, preferences, attitudes, culture, and climatic conditions.

Despite the large cost-effective potentials and the increased policy efforts to promote energy efficiency in households, the uptake of energy efficient technologies has often been slow. The discrepancy between profitable energy efficiency potentials and the actual market uptake, the so-called energy efficiency gap [8], [9] has been debated widely and controversially. A variety of market imperfections that prevent the adoption of energy efficiency technologies have been suggested including information asymmetries, split incentives, lack of interaction between user and producer, lack of awareness, lack of capabilities to define needs or respond to innovation [10].

While the factors that influence consumer behavior and the energy efficiency gap have been investigated rather extensively in the past years and the understanding of behavioural aspects has advanced considerably, these findings are often not sufficiently reflected in energy demand models. To date the vast majority of formal energy-economic modelling and analysis of energy futures has focused on technological change and on the economic impact of energy supply and use, with much less attention on behavioural drivers [11]. In these models, behavioural barriers are frequently implemented by choosing particularly high discount rates, arguably reflecting not just economic rationale but the whole set of non-monetary barriers [12] The empirical evidence for choosing a particular level of discount rates, however, is weak, at best. In particular, the models do not account for the fact that discount rates, which essentially capture time discounting ("impatience") and risk preferences may vary by household characteristics, countries, and energy efficiency technologies. The impacts on the modeling results can be dramatic and convey policy messages which may wrongly inform the policy sphere.

The aim of this paper is to provide an overview of recent studies on behavioural factors that influence the purchase decisions and to link the findings to energy demand modelling.

Logit approach in energy demand modelling

Most energy demand models are based on a logit approach to describe the individual purchase decisions for energy related technologies or services. The logit model stems from early works (see e.g. [13]–[15]) and is the most widely used discrete choice model [16]. In the simplest form of the logit approach, the probability P_{ni} that decision maker n chooses option i is given by the following equation.

$$P_{ni} = \frac{e^{\lambda U_{ni}}}{\sum_{j=1}^{N} e^{\lambda U_{nj}}}$$

Equation 1

The sum in the denominator of the equation runs over all available options, λ denotes the scale parameter that accounts for the magnitude of the observed part of the utility function U_{ni}, which is given by the following equation.

$$U_{ni} = b_{n1} PP_i + b_{n2} EC_i + b_{n3} MC_i$$

Equation 2

The observable part of the utility function typically includes the purchase price PP, the energy cost EC and, where applicable, the maintenance cost MC. The parameters b determine the extent to which the decision maker values each of the elements of the utility function, where $b \leq 0$.

For household appliances, the maintenance cost of options with different energy efficiency can typically be neglected, such that eq.Equation 2 reduces to

$$U_{ni} = b_{n1} PP_i + b_{n2} EC_i$$

Equation 3

In this framework, the market share of a given option i (e.g. A-labelled refrigerator) is determined by its total cost of ownership with respect to the other available options (e.g. refrigerators in the labeling classes A+, A++ and A+++), the sensitivity parameter λ and the relative weight that the consumer puts on energy cost versus purchase price ($b_2/b_{\square}$).

Assuming constant discount rates in time, this can be formulated as a net present value calculation with

$$\frac{b_{n1}}{b_{n2}} = \frac{d}{1-(1+d)^{-LT}}$$

Equation 4

Where d is the discount rate and LT is the lifetime of the appliance.

For illustrative purchases, in Figure 1-Figure 3 we assume a market with only two competing options, where for option 1 the energy costs over the product lifetime equal the purchase price, whereas for option 2 the ratio is 60%/40%. This means that option 1 is more efficient than option 2. We display how the market share of option 1 depends on the difference to the total cost of ownership (TCO) of option 2 and the parameter λ and the consumer preferences. In **Error! Reference source not found.**, it is assumed that consumers do not have a preference for either purchase price or energy cost. In **Error! Reference source not found.**, we assume that consumers place a higher value on purchase price, whereas in **Error! Reference source not found.** we assume that consumers value the energy cost more than purchase price.

From Figure 1-Figure 3 it becomes clear that in comparison to the case of consumers with balanced preferences between energy cost and purchase price (**Error! Reference source not found.**), shifting preferences towards purchase price (**Error! Reference source not found.**) leads to a market share that is lower than the most cost-effective level, whereas shifting the preferences towards energy cost (**Error! Reference source not found.**) leads to a market share that is higher than the cost-optimal level (from the consumer perspective).

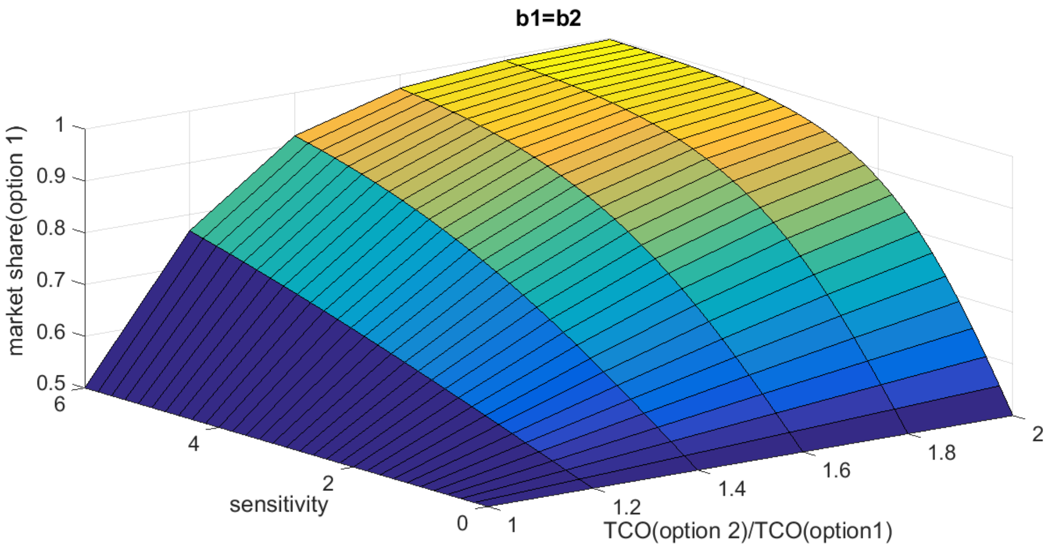

Figure 1: Market share of option 1 with equal preferences for energy cost and purchase price. The market share increases with increasing ratio of the total cost of ownership between the two options as well as the sensitivity.

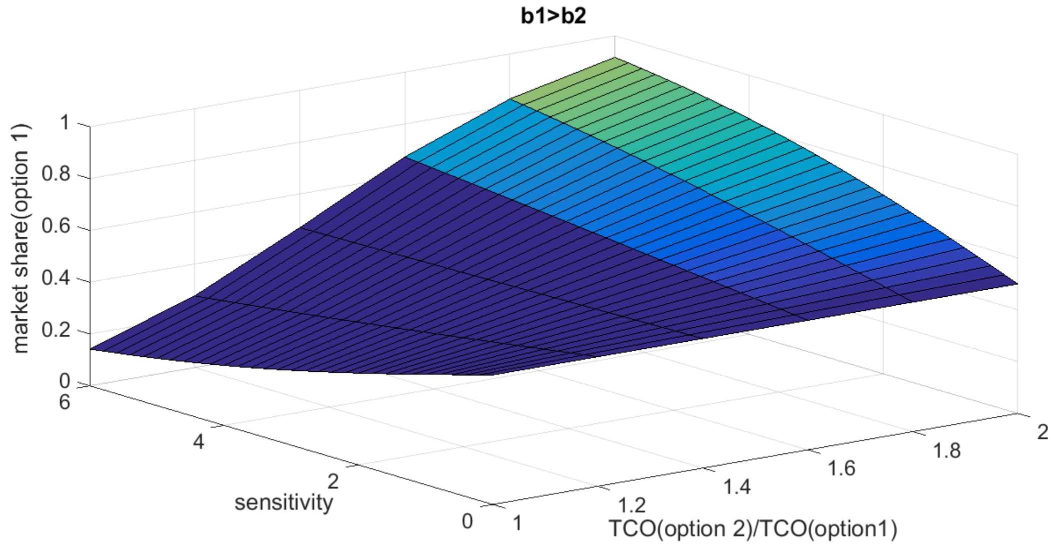

Figure 2: Market share of option 1 assuming consumer preferences for purchase price vs. energy cost. The market share increases with increasing ratio of the total cost of ownership between the two options as well as the sensitivity, however, the overall market share is considerably lower than in Figure 1.

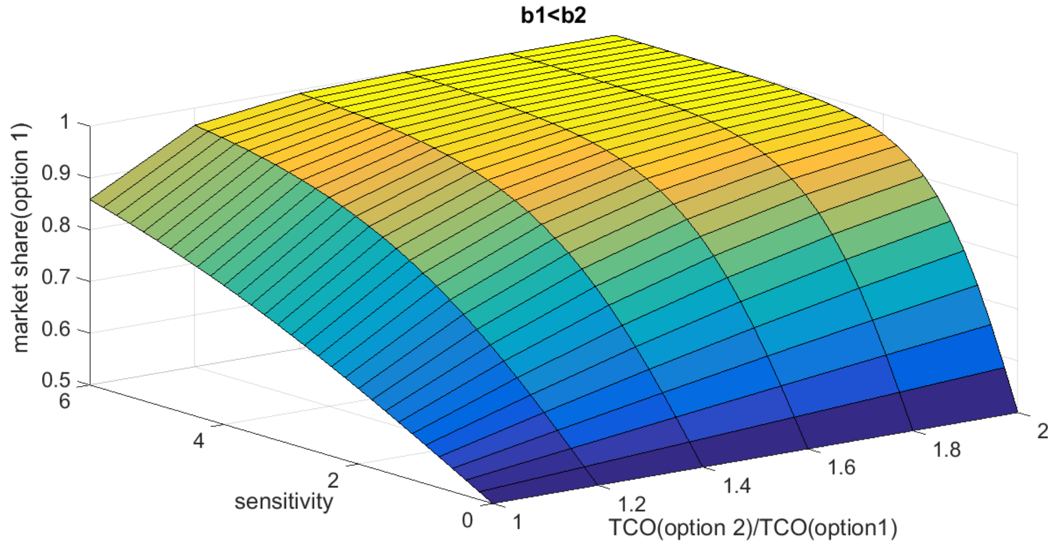

Figure 3: Market share of option 1 assuming consumer preferences for energy cost. The market share increases with increasing ratio of the total cost of ownership between the two options as well as the sensitivity, however, the overall market share is considerably higher than with equal preferences (Figure 1).

Individual, implicit, social and market discount rates

The discussion on the use of discount rates in energy demand modelling includes four different concepts of discounting that lead to differing results. These will be discussed in more detail it this section.

Market discount rates

The market discount rate denotes the prevailing rate of interest offered on cash deposits based on the duration and amount of deposits. In the case of credit-financed energy efficiency measures, the market discount rate denotes the prevailing rate of interest on loans based on the duration of the loan and the type of security offered.

Social discount rates

The social discount rate serves the purpose of evaluating the investments and benefits of policy from intergenerational perspective. It is often the case in environmental policy that implementation of policy is associated with high upfront costs and long time period for return of benefits. Because the social discount rate implies how to evaluate the future generation to the current generation, finding the appropriate social discount rate generates an answer to an ethical question [17]. This concept is widely used in governmental reports for evaluating environmental policy in social perspective.

Individual discount rates

In this article, individual discount rates denote such discount rates that individuals state to have, e.g. in stated preference studies. In experimental studies, the participants are typically asked for their preferences when offered a certain amount of money today or a different, typically larger, amount of money after a given time. The results are then used to calculate the individual discount rates. However, the results differ rather strongly depending on the experimental settings as well as the target groups.

With respect to the diffusion of energy efficiency appliances, it is important to observe that stated preference experiments reveal a considerable difference between the preferences with regard to losing money than for receiving money. When investing in an energy efficient appliance, the relevant question is if an individual is *willing to pay* a given amount of money in order to (at a later point in time) *avoid losing* money on unnecessarily high energy costs.

In the literature, there are considerably fewer studies that address the willingness to pay to avoid future loss of money. As it has been shown that individuals have differing preferences for winning than for losing money, it is essential to further investigate the willingness to pay to avoid future loss of money and to adapt policy measures to address this.

Implicit discount rates

Implicit discount rates are derived from observed purchasing behavior and therefore reflect all possible monetary and non-monetary barriers. For example, if we assume that eq.Equation 3 correctly describes the investment decision, the parameters β can easily be derived by fitting the equation to observed market data. Using eq. 3, the implicit discount rates can be calculated.

Deriving implicit discount rates from market data typically reveals very high discount rates for several reasons: First of all, eq.Equation 3 reflects the observable part of the utility function, assuming that all errors follow the logit distribution and are covered in the parameter λ. However, this condition is not necessarily fulfilled when individual choose non-efficient appliances due to a lack of knowledge about energy costs or a lack of upfront capital to buy more expensive efficient appliances. Secondly, the market data reflects purchase decisions under a given policy framework. If policies change, past market data does not appropriately reflect decision-making as policy may have a strong influence on decisions (see following section).

Discount rates in energy demand modelling

Most energy demand models, in one way or another, make use of discount rates to reflect the market interest rate, the time preferences of consumers, or any other barriers that prevent consumers from buying the option with the lowest total cost of ownership. As different models include different aspects in their discount rates and use different methodologies to determine it, it is unsurprising that discount rates vary significantly between different energy demand models. Frederik et al. (2002) reviews numerous existing studies on estimating discount rates that individuals apply [18]. They conclude that individuals apply different discount rates depending on the goods and the contexts in which they stand. Table 1 presents a (non-comprehensive) list of energy demand models and the discount rates that are applied.

Table 1 List of Energy Demand Models and Discount Rates Used in Studies

Model	Study	Countries	Context	Discount rates
BLUE	Strachan and Warren [19]	UK	Social rate	3.5%
MARKAL	Ybema and Kram [20]	Netherlands	Real discount rate	5%
			Investment decisions	10-30%
	Kannan et al. [21]	UK	Global discount rate	10%
			Hurdle rate for high efficiency class	25%
CIMS	Sadownik et al. [22]	Canada	Market discount rate	10%
			Financial support scenario	8%
NEMS	U.S. EIA [23]	USA	Implicit discount rate: Refrigerator	10%
			Implicit discount rate: Room Air Conditioner	42%
			Implicit discount rate: Central Air Conditioner	25%
			Technology case scenario	7%
REEPS	Hwang et al. [24]	USA	Implicit discount rate: Refrigerator	69%
			Implicit discount rate: Freezer	91%
			Implicit discount rate: Dryer	120%
			Implicit discount rate: Dishwasher	111%
			Implicit discount rate: Washing Machine	391%
			Calculating the present value of operating cost	40%
PRIMES	De Bruyn and	EU	Reference scenario	17.5%, 12%

	Warringa [25]			from 2020
			Ambitious EE policies	Further reduced to 10% from 2030

Influence of energy efficiency policy on discount rates

Energy policy can address consumer decisions and therefore the implicit discount rates in various ways. Economic instruments such as subsidies for appliances with high energy efficiency decrease the purchase price the consumer has to pay and thus favour the market diffusion of high-efficient appliances. Information strategies such as energy labelling address market failures related to a lack of knowledge about energy costs and can address behavioural issues. Energy efficiency standards such as the ecodesign directive can help to address market failures such as principal-agent problems, behavioural issues as well as information failures. Labelling has an influence on the investment decisions of consumers, directing preferences towards more energy-efficient devices [26]. Without Energy Labelling (or when most products have reached the highest Labelling class), consumers lack information about the life-cycle costs of appliances. A number of recent studies show that information on life-cycle costs has a significant effect on the investment decisions of consumers and contributes to lowering the discount rates for residential appliances [27], [28].

Market discount rates can to some extent be influenced by policy, if risk is minimized and/or access to low-interest capital is provided. For appliances this is not very relevant, however, for buildings and industry it may be.

Individual discount rates are likely to be able to be addressed by policy as a number of studies have shown that the kind of information provided and the framing change the willingness to pay of decision makers. The willingness to pay a higher purchase price can therefore be increased if knowledge on the expected savings is presented and by displaying environmental or social benefits.

The implicit discount rate is strongly affected by policy, as it includes all (monetary and non-monetary) barriers that prevent the purchase of energy efficient appliances, including lack of knowledge, lack of capital, etc. If the implicit discount rate is derived from market data it is essential that the underlying dataset includes the relevant policy measures.

Albeit it is difficult to exactly measure how energy efficiency policies influence consumers' decision making, a number of studies reveal that policies such as labelling have an impact on consumers to choose more energy efficient appliances to a certain extent. Table 2 summarises those studies and the findings.

Table 2 Studies on Influence of Energy Efficiency Policy on Consumer Behaviours

Study	Appliance	Country	Findings
Loads of green washing—can behavioural economics increase willingness-to-pay for efficient washing machines in the UK? [26]	Washing machine	UK	Labelling schemes have an influence on purchase decisions, however, supplementary information about running costs and emissions could increase the willingness to pay for energy efficiency further.
Subjective discount rates in the general population and their predictive power for energy saving behavior		Switzerland	High subjective discount rates (20% and above) Socio-demographic factors such as income and education might be

[29]			negatively correlated to the discount rates. No concrete relation between the levels of discount rates and energy saving behaviours was found.
Labeling energy cost on light bulbs lowers implicit discount rates [30]	Lighting	USA	Providing estimated annual cost information reduces implicit discount rate by a factor of five, however, even with cost information provided, consumers continued to use implicit discount rates of around 100%.
Willingness to pay and price elasticities of demand for energy-efficient appliances : Combining the hedonic approach and demand systems [31]	Dish washer	Basque country (Spain)	The price premium for energy efficiency that consumers are willing to pay is estimated at about 15.6% of the final price, that is about 80€ on average. The demand for labelled appliances is more elastic than the demand for non-labelled ones.
How consumers respond to environmental certification and the value of energy information [32]	Refrigerator	USA	Consumers respond to the energy star certification and electricity costs in decision-making. Consumers are heterogeneous in that they respond to different types of energy information: 1. Respond to continuous measure of electricity costs, 2. Respond to the ES certification, and 3. Energy information does not matter. Those who respond to ES have a high willingness to pay for the label.
Effect of Energy and Environmental Policies on Greenhouse Gases for 1990–2000 (in Dutch) [33]		Netherlands	Introduction of energy efficiency labels increases the awareness of energy cost savings and it leads consumers to make decisions more sensitive to higher prices.
Nudging Energy Efficiency Behavior: The Role of Information Labels [34]		USA	Simple information on the economic value of saving energy is the most important element. Additional information on the amount of energy use and CO_2 emissions had lesser impact on decision-making though they have incremental value. Using individual discount rates (11 and 20%) the current EnergyGuide label came very close to guiding cost-efficient decisions, on average. However, using a uniform 5% for discounting, the

			EnergyGuide label led to choices that result in a one-third undervaluation of energy efficiency.
Under the Influence? Consumer attitudes to buying appliances and energy labels [28]	White goods	UK	Majority of consumers are influenced by the A-G rating while there are other factors such as price that have a great impact. For consumers who are not influenced by the energy rating, they either were not aware of, or didn't understand the label. In other cases, they didn't think the energy savings would sufficiently cover the higher upfront costs.
The influence of eco-labelling on consumer behaviour – results of a discrete choice analysis for washing machines [35]	Washing machine & Light bulbs	Switzerland	Consumers have higher willingness to pay for A-labelled energy efficient products. For a low-involvement decision-making product (i.e. light bulb), a label plays more important role than for a high-involvement product. Consumer's willingness to pay for A-labelled products is higher than the actual cost savings expected over the lifetime of the product.

Implications for energy demand modelling

In this section we illustrate the importance of user preferences towards purchase price (reflected in high discount rates) in energy modelling. We FORECAST-Residential, a vintage stock model with detailed coverage of the most relevant energy using household appliances to analyse nine scenarios with varying assumptions on the sensitivity of consumers to the utility function (eq. 3) and the ratio between the parameters b1 and b2, which describe consumer preferences towards purchase price and energy cost, respectively.

Description of the FORECAST-Residential model

We use the model FORECAST-Residential[1,2], a bottom up energy demand model covering the EU-28 as well as Norway, Switzerland and Turkey, in which the energy demand is simulated on individual member state level, distinguishing a variety of energy demand end-uses. For residential electricity use, the model covers large appliances (refrigerator, freezer, dishwasher, washing machine, and dryer), cooking, lighting, ICT appliances (television, set top boxes, laptop and desktop computers, monitors, modems) and air conditioning.

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[1] FORECAST (FORecasting Energy Consumption Analysis and Simulation Tool) is a modelling platform that captures the final energy demand of the industry, residential, tertiary, transport and agriculture sector (http://www.forecast-model.eu).

[2] In addition, FORECAST-Residential also captures the useful and final energy demand for heating purposes, which are not part of this study [37]

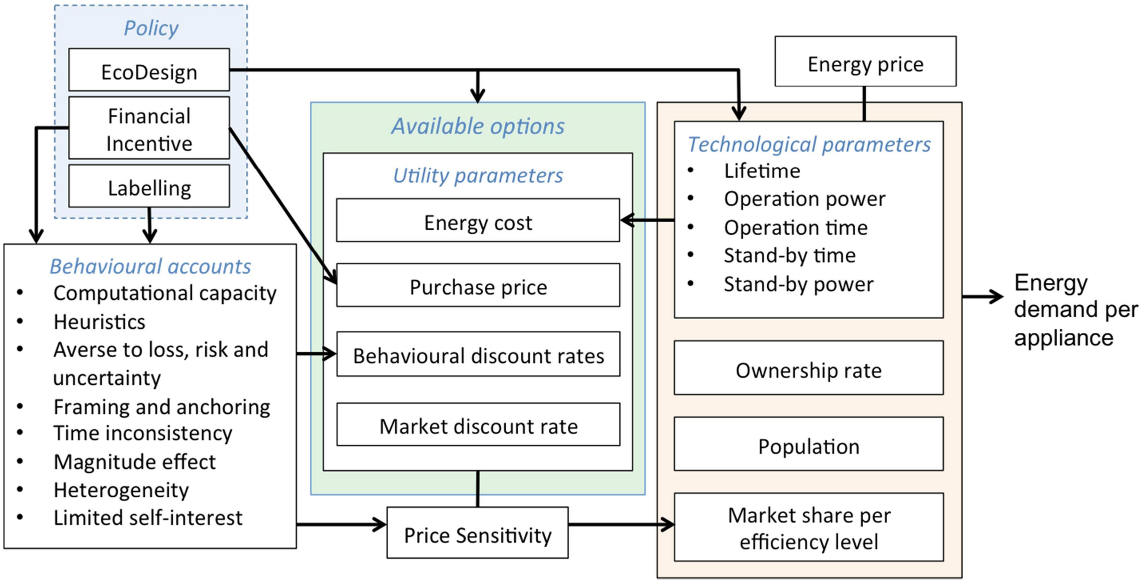

Figure 4: Overview of FORECAST-Residential Model Approach

FORECAST-Residential is a vintage stock model allowing a detailed modelling of the stock turnover, taking into account autonomous and policy-driven innovations in energy efficiency of appliances, lighting and air conditioning over the years. For each year, the end-use types that are available on the market are exogenously specified, taking into account policy requirements. The alternative choices that are available on the market differ both in energy efficiency and in their respective purchase prices.

The market share of each appliance type is modelled as a result of individual investment decisions. The investment decisions are modelled as a discrete choice process, where household decision makers choose among alternative technologies competing with each other (see e.g. [36]).

In order to reflect the policy effects on decision-making processes, what is conventionally described as implicit discount rates is separated into three variables: price sensitivity, market discount rate and behavioural discount rates. It is common in logit models to include an additional variable intangible cost to reflect non-monetary aspects. Non-monetary attributes such as brands, additional features and design are indeed important factors influencing the decisions. These are, however, also additional factors that are non-monetary. Instead of including additional variable within the utility function, adoption of price sensitivity as an overall factor of utility function separates the effects of non-monetary attributes of the product from the monetary effects.

Behavioural discount rates reflect consumers' pure time discounting (individual discount rates), market failures and any other behavioural aspects from which consumers drive utility based on investment and energy costs. Therefore behavioural discount rates should vary for different socio-economic backgrounds and be sensitive to price changes as well as policy. For instance, the changes in investment costs by financial incentive will not only reduce the investment cost but also influence the behavioural discount rates.

The effects of energy labelling enter the model in several ways. One way is that labelling provides information on energy consumption, driving consumers to be more future-oriented. This is expected to influence the behavioural discount rates, giving more preference to energy cost. Other ways are labelling being utilised as a decision heuristic or more values being associated to high-labelled products. These two effects of labelling can be reflected in the energy demand model by increasing the price sensitivity.

Ecodesign eliminates less efficient appliances from the market, limiting the product choice pool, which is reflected as controlling the available products in Figure 4. The FORECAST-Residential model has a separate mechanism to reflect availability of technologies in the market. The effects of ecodesign is, therefore, not reflected through the logit model but can be explicitly demonstrated through the market availability mechanism.

Results for differing levels of discounting

We analyse the effect of the sensitivity of consumers to the total cost of ownership as well as their preference for purchase price vs. energy cost by projecting the electricity demand for household appliances in Germany using different assumptions on the parameters that control these aspects.

Figure 5-Figure 7 show three cases of price sensitivity applied: low, medium and high sensitivity respectively. Within each sensitivity case, the ratio of logit parameters (b_2/b_1) is adjusted to 0, 0.5 and 1, denoting total nine different scenarios. As the ratio is close to 1 it implies that consumers take both purchasing price and expected energy costs equally into decision-making, therefore, resulting in a "rational" decision. The results are shown in total electricity consumption (PJ).

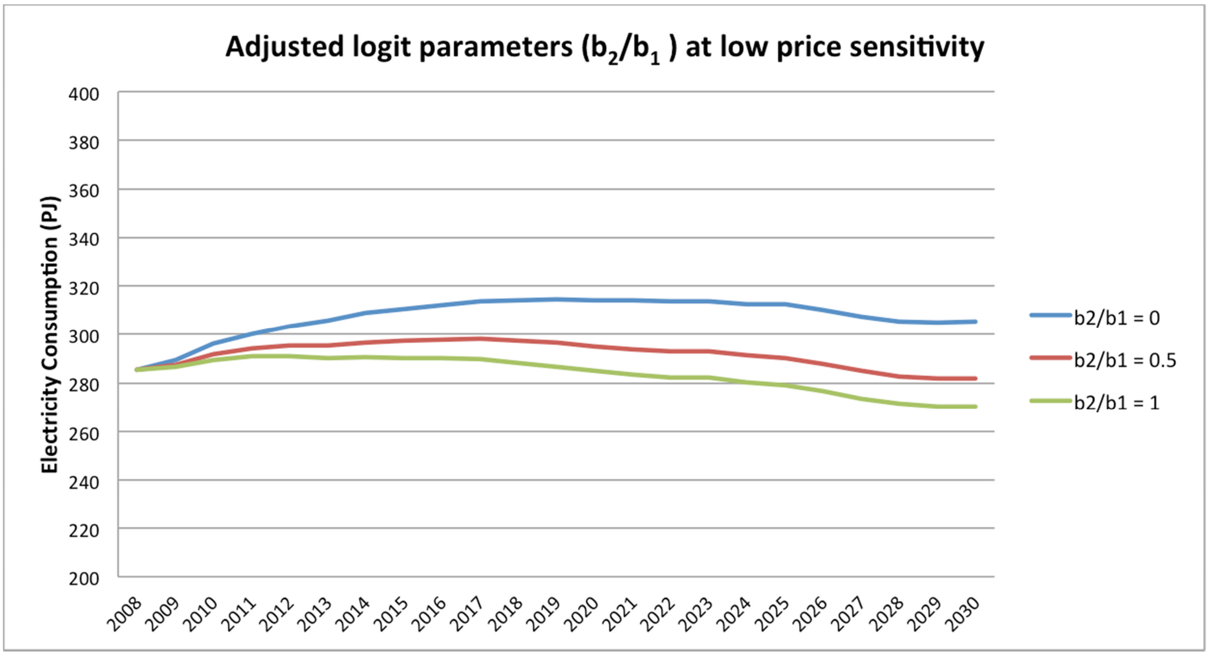

Figure 5: Electricity Consumption assuming low price sensitivity and varying preference for purchase price and energy cost.

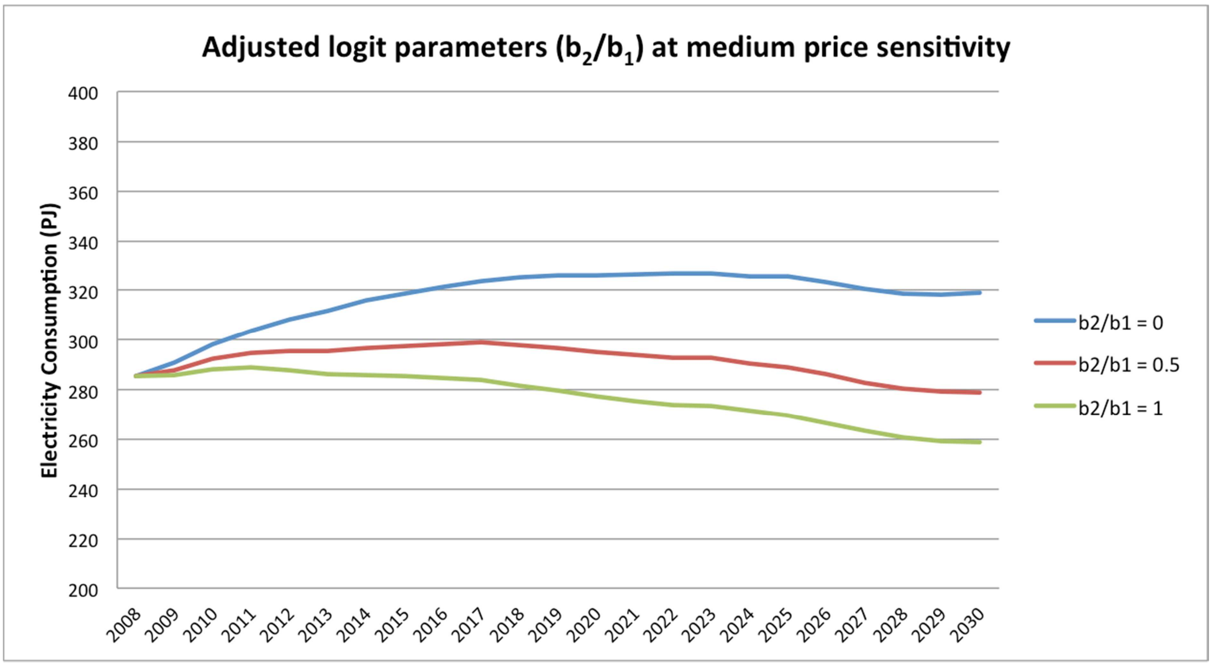

Figure 6: Electricity Consumption assuming medium price sensitivity and varying preference for purchase price and energy cost.

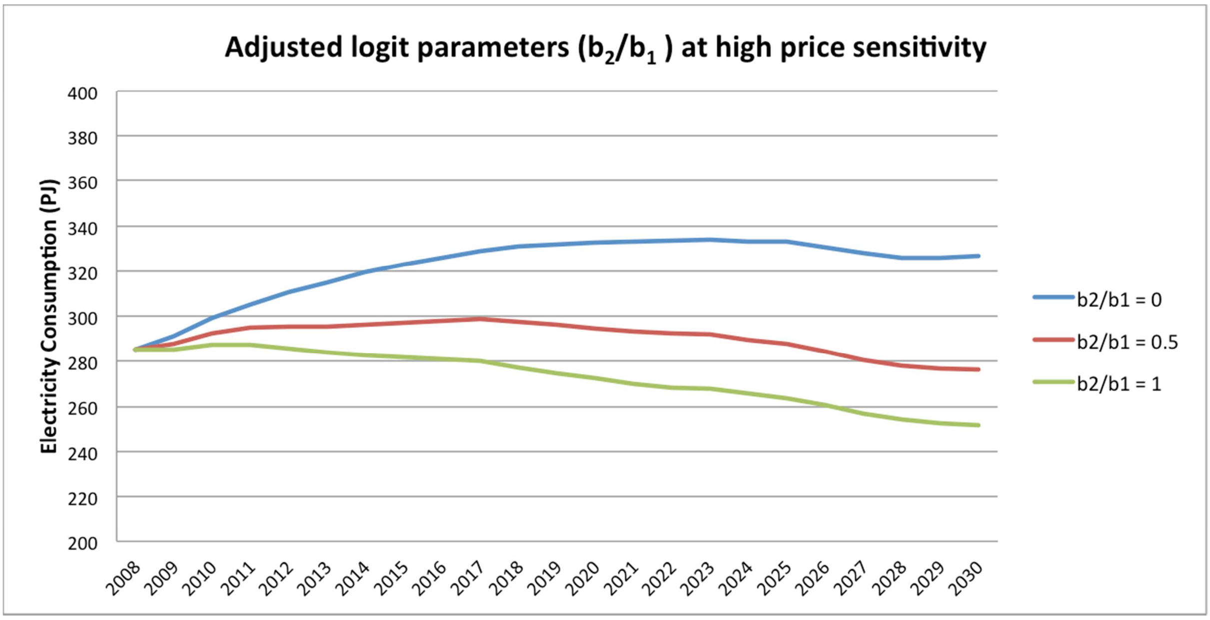

Figure 7: Electricity Consumption assuming high price sensitivity and varying preference for purchase price and energy cost.

In all three price sensitivity cases, the higher the preference is given to energy cost, the lower the expected electricity consumption shows throughout the timeline. As consumers are more sensitive to price, the range of expected total consumption widens. For example, at low price sensitivity (**Error! Reference source not found.**) the gap between the ratio 0 and 1 is expected to be about 40 PJ in 2030, whereas at high price sensitivity (**Error! Reference source not found.**) the gap doubles to around 80 PJ.

The results of the nine scenarios are summarized in Figure 8, where we show the cumulative savings between 2008 and 2030 with respect to the “worst-case-scenario” of high sensitivity and strong preference for purchase price.

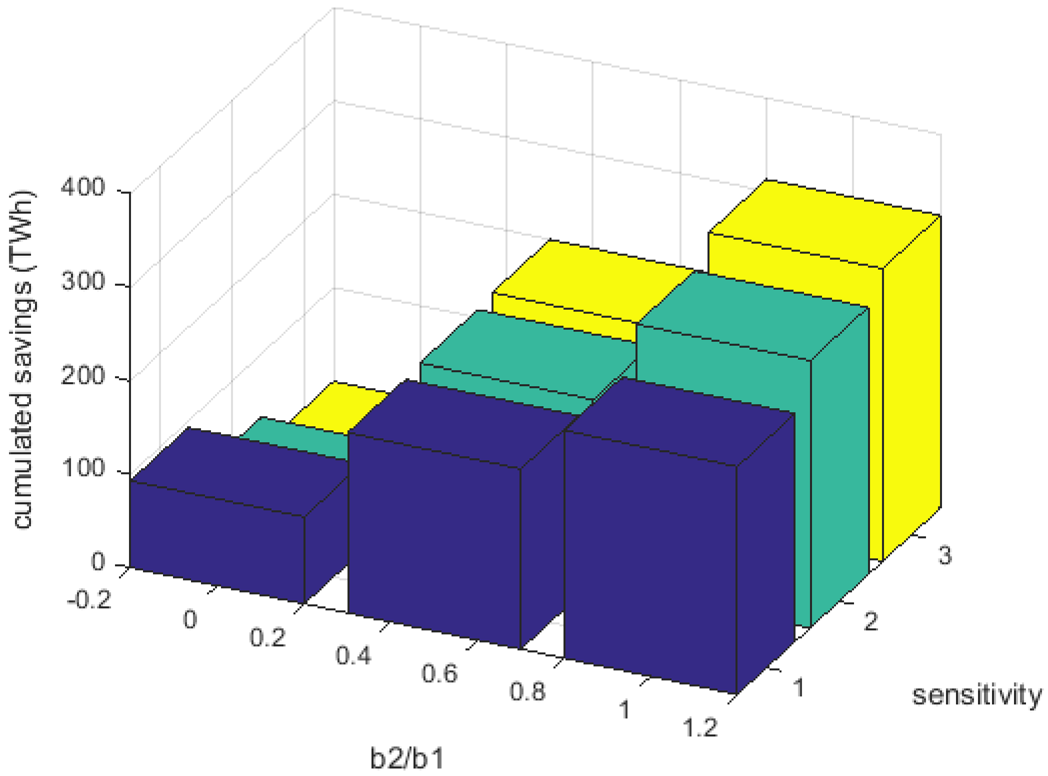

Figure 8: Cumulated electricity savings (2008-2030) with different sensitivities and preferences. For high sensitivity

Summary and Conclusions

We have illustrated the importance of the use of discount rates and consumer preferences for purchase price vs. energy cost in energy demand modelling by comparing nine scenarios with differing assumptions on these parameters. We show that the projected long-term demand for electricity for household appliances in Germany differs considerably when different discount rates are applied.

We have reviewed the literature on discount rates in energy efficiency decisions and draw the following conclusions for energy demand modelling and for policy making: On the one hand, it is essential to integrate the recent advances in understanding the role of behavioural aspects in investments in energy efficiency technologies in energy demand models. In particular, the influence of policy on such behavioural aspects should be reflected in any model used for policy evaluation. This could be done by disentangling the different concepts of discount rates found in energy demand models into segments that reflect monetary and non-monetary aspects. Furthermore, the calibration of the energy demand models has to be performed with datasets that reflect the current policies, as otherwise discount rates are overestimated as barriers that have already been addressed. On the other hand, the results confirm that an essential task in energy efficiency policy is to address behavioural aspects and direct purchase decisions towards appliances with higher energy efficiency.

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Trends for residential electrical energy use in Australia

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Abstract

Electric energy consumption in the residential sector has been decreasing in Australia since 2009 and many have attributed improved Minimum Energy Performance Standards (MEPS) and Energy Labelling to this decline. A recently completed comprehensive update and re-design of the energy end-use model for Australia and New Zealand, has provided insights into the energy and demand impacts of various appliance programs and changes to market characteristics, over the last 15 years.

The 2014 Australia and New Zealand Residential Baseline Study (RBS) examines the historical energy end use trends to 2013 and makes projections to 2030. Research on the market factors, appliance attributes, building efficiency and use of equipment in the residential sector has provided deep insights into the potential causes of now declining energy use. The research has utilised up to 20 years of sales data, matched with appliance attribute information (efficiency, size, etc.) of appliances, lighting and building thermal efficiency, to produce a stock and linked energy model of Australia and New Zealand. Analysis of this model suggests that factors which have contributed to the observed energy use trends over the last two decades include; increased use of efficient lighting, declining refrigerator energy use, fuel switching from electricity to gas water heaters and water efficiency measures to reduce hot water use. Even TVs have shown a decline of 40% in operating power over the last 4 years.

Many of the appliance and equipment used in households have been subject to MEPS and labelling programs, with significant increases in scope and stringency since the late 1990s. These programs are now impacting on the overall energy use in Australia and New Zealand, with dramatic effects that were not considered in earlier forecasts or planning by energy authorities. This paper examines the major factors contributing to trends in electricity energy consumption by end-use, such as efficiency programs, changes in market characteristics and household usage. It also provides forecasts of the overall residential electricity consumption to 2030, accounting for currently implemented efficiency programs and market trends.

Introduction

The 2014 Australia and New Zealand Residential Baseline Study (RBS) examines the historical energy end use trends up to 2013 and makes projections from 2014 to 2030. Two similar studies were conducted, in 1999[1] and 2008[2]. The RBS utilises a ‘bottom up’ energy end-use model of the residential energy sector, divided into major end-uses (i.e., appliances, hot water, etc.), categories of equipment (i.e., televisions, electric water heaters, etc.) and products (i.e., plasma TV, small water heater, etc.). The recent 2014 update of the RBS expands on earlier studies by including additional products and utilises a slightly different approach to the stock modelling. This 2014 study uses updated information and research derived from several projects undertaken since the 2008 study commenced (the 2008 study used data available up until 2005).

Although the RBS model and forecast includes all major residential fuels (electricity, gas and wood) and associated end use appliances/equipment, this paper reports on the results for electricity only, in order to provide a detailed examination of the trends. The coverage of all the end use trends by fuels in not possible in the space limitations for this paper, however the final RBS report provides the complete results[3].

The overall electricity use in the residential sector in Australia (excluding solar electric PV self-consumption) has declined by almost 3% in 2012-13 compared to 2010-11 financial year [4]. This is the first time in Australia’s recent history that electricity use has declined over two subsequent years. There are possibly many factors contributing to this decline in overall electricity use, including the improvement in efficiency of appliances, improvements in the thermal efficiency of buildings and fuel switching (including to gas appliances or solar hot water). Decline in usage is also attributed to reductions in the services supplied (such as more efficient shower heads reducing hot water usage and behavioural changes in response to increased electricity prices. When examined on a per household basis, the reduction in electricity use is even more pronounced (see in Figure 3).

In comparison, total gas usage has not shown a decline in energy consumption, plus there has not been a substantial upgrade to the standards, labelling or efficiency of gas appliances. Therefore the focus of this paper is on electricity energy use and the contributions to changes in consumption by residential consumers of electricity. The paper provides an overview of the methodology, research and data used to develop the RBS and then assesses each end use in turn.

Methodology and research

Methodology overview

The underlying methodology on which the residential energy end-use model and study is to be based is classified as a bottom-up engineering model [5]. It involves calculating the energy end-use consumption at the individual level and aggregating these consumptions to estimate the total locality or network consumption.

At the heart of this approach is the calculation that for each energy end use:

*Total Energy Consumed = Stock Numbers * Unit Energy Consumption (UEC)*.

Determining the stock number of energy end-use equipment is undertaken by stock models which are effectively databases that keep a running tally of the number of equipment installed on a year by year basis. The stock in any year will be the sum of all past stock sales, less retirements of equipment.

The next aspect of the energy modelling is determining the value of the Unit Energy Consumption (UEC) for each end-use to be used in the residential energy end-use model. At its most basic level, UEC is determined by:

*UEC = Hours of usage * Unit Energy Input,* or

*UEC = Hours of usage * Unit Capacity * Unit Efficiency.*

The energy use of residential equipment can be calculated from these formulae, or from a variation of these formulae for more complex products operating in different modes or different measurement and usage metrics (such as wet appliances where UEC is a function of the usage per cycle). For products with multiple modes (e.g., products which have a standby energy consumption element), energy consumption while in operating mode must be separately calculated and added to obtain the total energy consumption in all modes. Although there are several different modes of operation found in appliances these have been condensed to the modes shown in Table 1.

Table 1: Modes of operation used in the RBS

Mode	Description
Operation 1	Main operation mode - heating mode in space conditioning equipment.
Operation 2	Main operation mode - cooling mode in space conditioning equipment
Auxiliary	Auxiliary mode used by some appliances such as energy use by fans in gas heaters
Standby	The modes that are non-operating (standby/off), but consuming power.

Space conditioning energy use requires special attention due to the impact of climate on usage and equipment efficiency, and the interaction of the thermal efficiency of the building shell with the usage of the equipment. There are many methods for estimating space conditioning energy use and demand. Broadly they can be divided into the measurement/metering based approaches (billing, metered data, hours of usage analysis), building thermal modelling, and engineering algorithm approach as identified by Stern [6]. In Australia there is insufficient data to use measurement/metering based approaches so the mixed engineering/building thermal modelling, using AccuRate software developed by CSIRO [7], which has previously been used to predict energy use, is used in this study. The annual variation in climate conditions has not been included in the modelled energy use; however climate variation by household location is accounted for in the RBS model.

A systematic approach to the model development was used to ensure all end-uses were considered and the model was developed by focusing on products in each end use. The end-uses and their categories (where appropriate) are listed as follows:

- Water heating
- Space conditioning
- Appliances
- White Goods
  - IT and Home Entertainment
  - Other Equipment
- Cooking
- Lighting.

Common functions, which will supply data to or accept data in, regarding the products are:

- Building Stock (including thermal demand requirements)
- Energy usage aggregator
- Peak demand calculator (not discussed in this paper)
- User Interfaces for data input/scenario testing.

A schematic of the end-use model is provided in Figure 1.

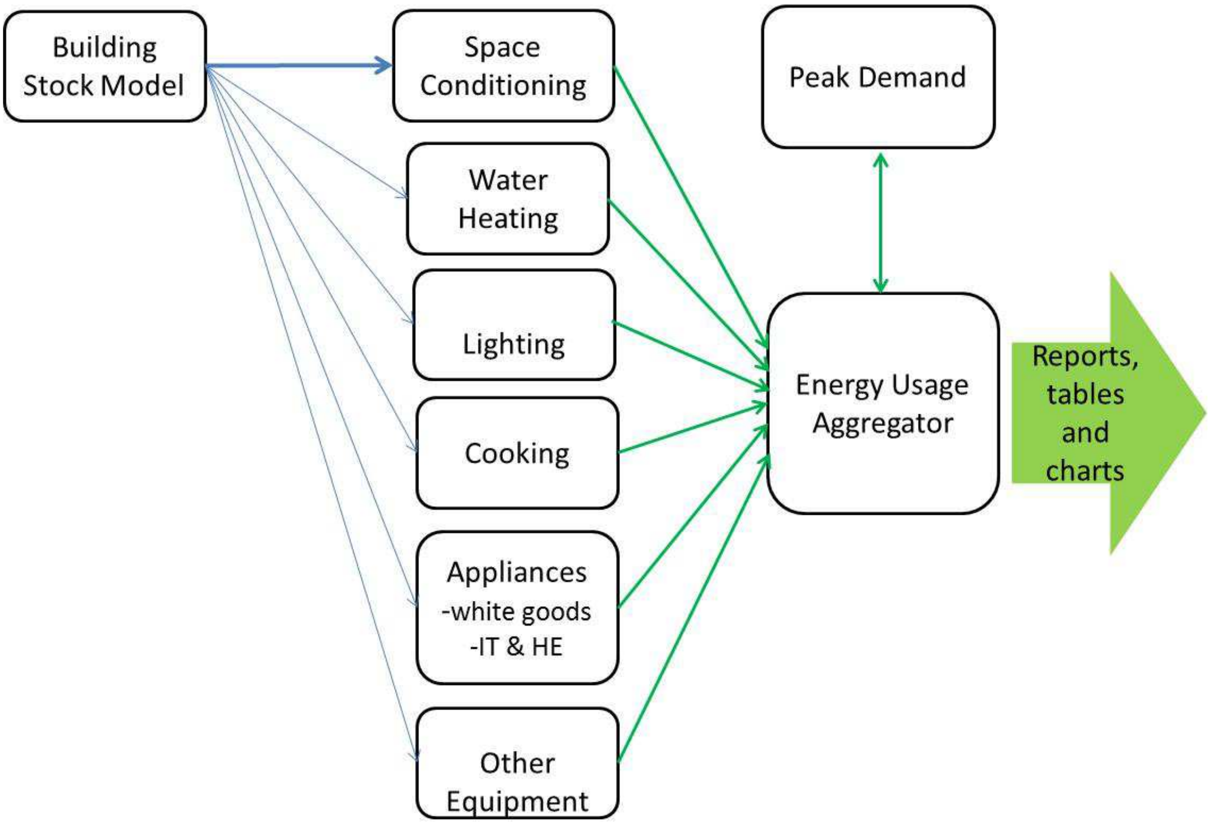

Figure 1: Schematic of energy end-use model modules and linkages.

The end-uses and categories, along with the typical equipment included in the model are shown in Table 2. The model calculates the impact of over 110 separate products.

Table 2: End-uses and categories with typical equipment used in the RBS

End-use & category	Equipment/Products included
Space Conditioning	Air conditioning (heating and cooling), fans, resistive electric heating

Water Heating	Electric storage, solar electric, heat pump water heaters
Cooking	Cook-tops, electric oven, microwave oven
Lighting	Incandescent, halogen, LED, CFL
Appliances - White goods	Refrigerators, freezers clothes washers clothes dryers dishwashers
Appliances – IT&HE*	PCs, laptops, network equipment, printers, TVs, game consoles, set top boxes, DVD/BluRay, etc.
Appliances – other equipment	Pool pumps, spas, battery charging systems, other miscellaneous (cleaning appliances, irons, etc.), other misc. standby

*IT&HE = Information technology and home entertainment

Research and data sources

The model inputs for the each of the products take into account the current programs that are affecting future energy use (i.e., Minimum Efficiency Performance Standards – MEPS & Energy Rating Labels – ERL) and those that scheduled to be implemented (where a Decision Regulatory Impact Statement/RIS has been approved by the Government). Trends in take up of energy efficiency technologies, such as LED lighting, are also considered in the forecasting of product sales and of future changes in product efficiency. Usage by households of many products is derived from Australian Bureau of Statistics (ABS) surveys, including a recent survey of 12,000 households in 2012[8]. Household projections from the ABS have also been utilised.

The key attributes of the majority of significant equipment installed in households by year, including the average of their size and efficiency, was obtain from analysis of the sales data by model and from MEPS/ERL registration data,. Sales of products were estimated from this same data or derived from penetration data, such as that obtained from ABS surveys. Research on the impact of the building thermal performance and the proportion of the building stock with improved thermal performance was also undertaken as part of this study.

Electricity energy consumption by end use

Total electricity consumption

The total residential Australian electricity energy consumption is estimated to have increased from 50,000 GWh in 2000 to 59,000 GWh in 2008, and then declined to 56,000 GWh in 2013. However, the forecast period from 2014 shows further declines and then increase in the later part of the 2020's as shown in Figure 2.

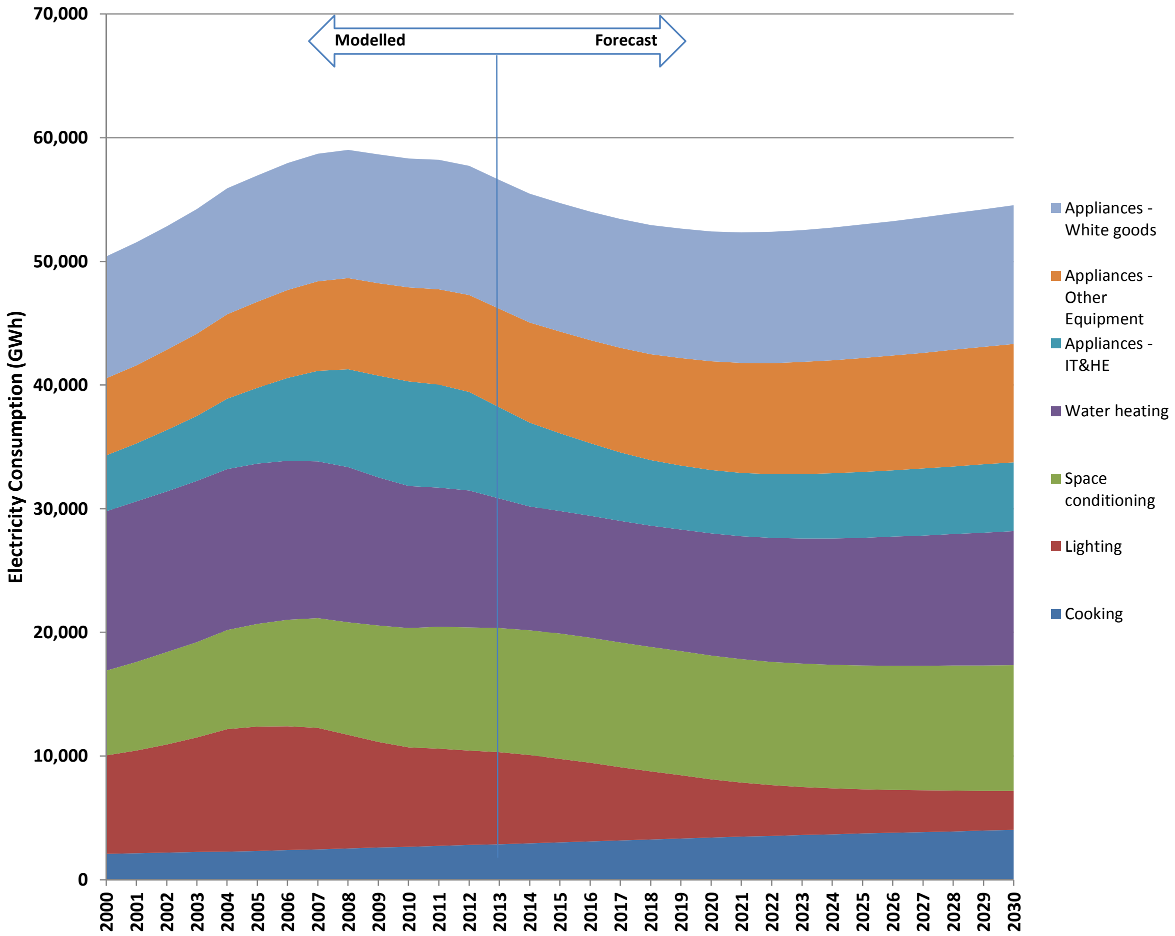

Figure 2: Estimated and forecast energy consumption by electricity end-use in Australia

Figure 3 shows that electricity consumption per household has increased till 2006 and then declines.

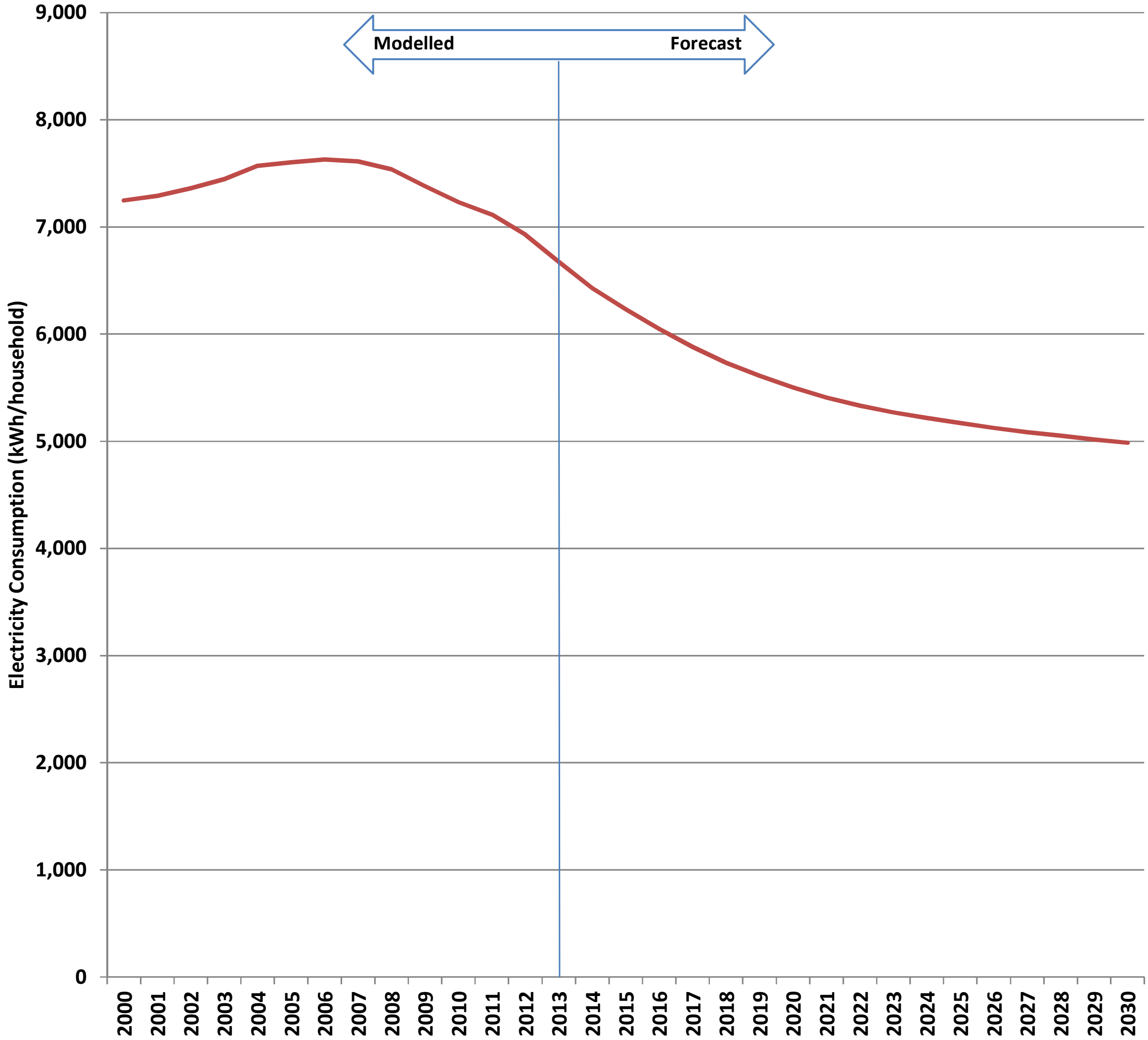

Figure 3: Estimated and forecast energy consumption per household in Australia

The main end-uses that are contributing to these interesting trends are explained in the following sections.

Space conditioning

Space conditioning electricity use by category displays an overall increase in energy consumption, but is then relatively stable from 2013 to 2030, as shown in Figure 4.

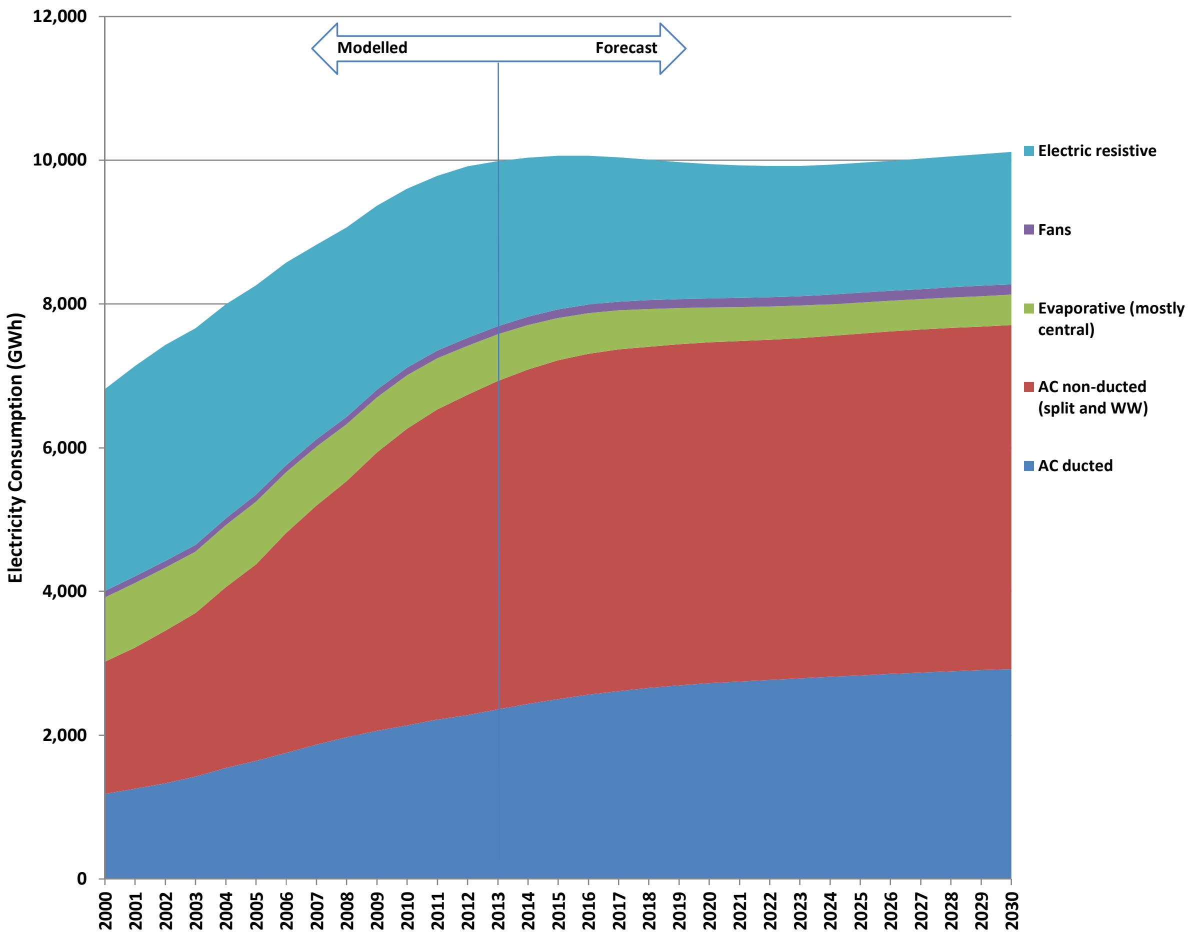

Figure 4: Estimated and forecast electricity consumption of space conditioning end-use in Australia

Factors contributing to energy use trends

Space conditioning equipment has shown a rapid increase in energy consumption from 2000 to 2012, which largely reflects the increase in ownership of air conditioners in Australian homes which has increased from 0.52 to 0.94 per household. The main reasons why space conditioning electric energy consumption has not increased further since 2012 are:

- the shift from electric resistive heating to use of reverse cycle air conditioners as heaters,
- an increase in the efficiency of air conditioners, from an average EER of 2.5 to 3.9 by 2013
- the impact of building thermal improvements due to the building code (in 2005 and again in 2011), and the federal governments home insulation program [9] during 2009-10 that insulated 1.2 million households (15% of total Australian households).

Lighting

Lighting demonstrates a rapid increase in energy consumption to 2006 and then is forecast to decline by over 60% to 2030, as shown in Figure 5.

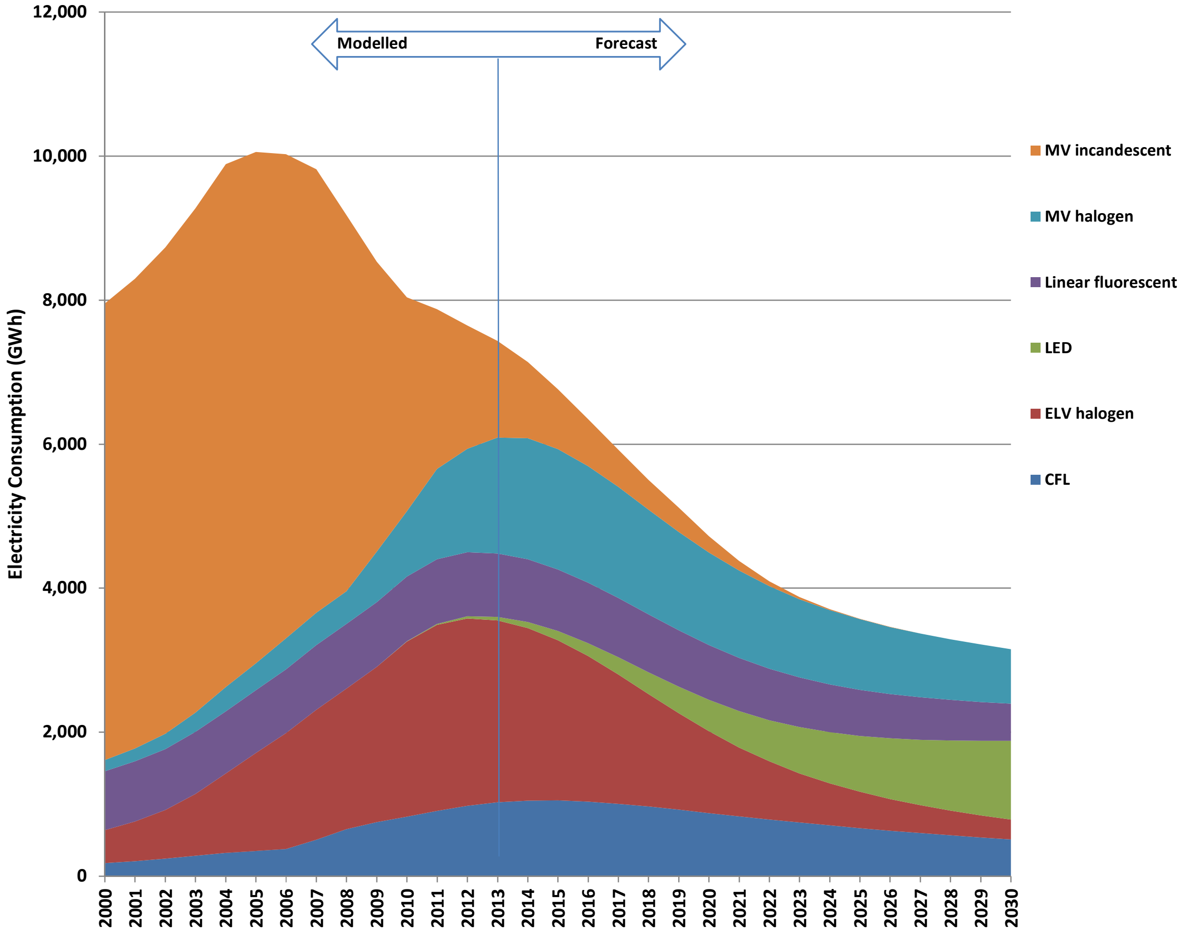

Figure 5: Estimated and forecast electricity consumption of lighting end-use in Australia

Factors contributing to energy use trends

Lighting energy use increased in the first half of the 2000s due to the increasing number of lights per household, especially of halogen downlights. However the national phase out of incandescent lamps and the state government based white certificate programs caused a market transformation and increased use of more efficient CFLs over the last decade. Now, total energy consumption for lighting is forecast to continue to decline as CFLs and LEDs slowly replace halogen lamps.

Hot Water

Hot water energy consumption was relatively stable to 2005 and then declined by over 20% to 2013. It is forecast to remain at this level till 2020, and then increase as shown in Figure 6.

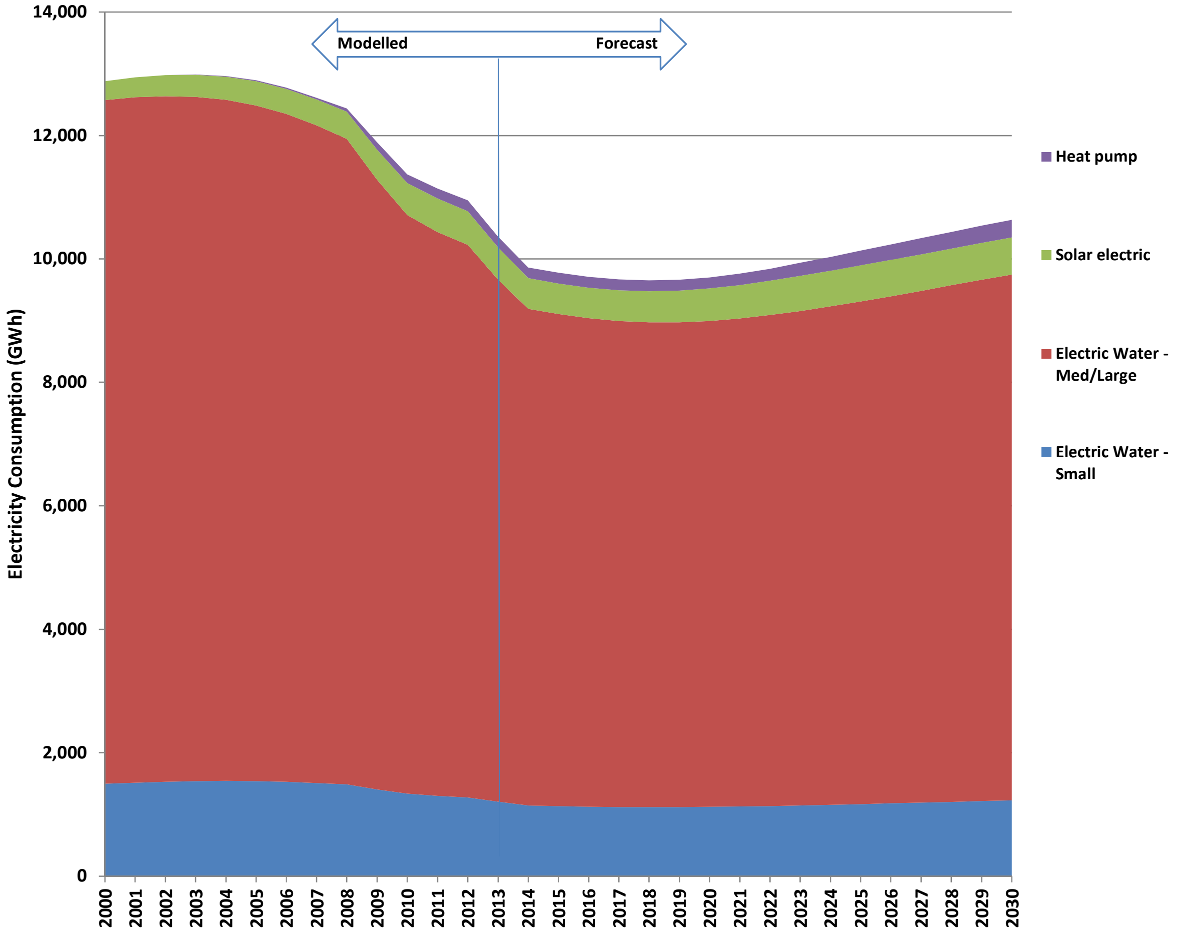

Figure 6: Estimated and forecast electricity consumption of water heating end-use in Australia

Factors contributing to energy use trends

A major factor contributing to the reduction in energy use in hot water, in the second half of the 2000s is the switching by consumers to gas, solar and heat pump water heaters, encouraged by incentives from state and federal governments and regulations that required new homes to install solar and heat pump water heaters. Average ownership of electric water heaters declined from 0.62 in 2000 to 0.46 in 2013. In addition, the introduction of a MEPS that reduced the heat losses from new electric storage water heaters by 30% in 1999, behavioural changes due to an extended drought and rapid take up of water efficient showers have also contributed to significant reductions in energy use per water heater. Research conducted for the RBS, utilising electricity distributor data on off-peak and controlled load water heaters, has found that the a decline in hot water use from water efficiency measures and changes in behaviour has contributed to approx. 10% of the reduction in total hot water electricity consumption in Australia.

The energy use by electric water heaters is forecast to increase slightly, as the fuel switching rate declines and no other MEPS or water efficiency measures are planned to be implemented. The financial incentives for solar and heat pump water heaters have also been significantly reduced resulting in sales reducing to pre-2007 levels. In one Australian state, the requirement to install solar or heat pump water heaters in new dwellings has also been rescinded, and the planned national regulatory measures to phase out electric water heaters have not been implemented.

Appliances – White goods

White goods electricity use by category shows a slow increase in energy consumption to 2010, then stabilises and is forecast to increase again from 2018 to 2030, as shown in Figure 7.

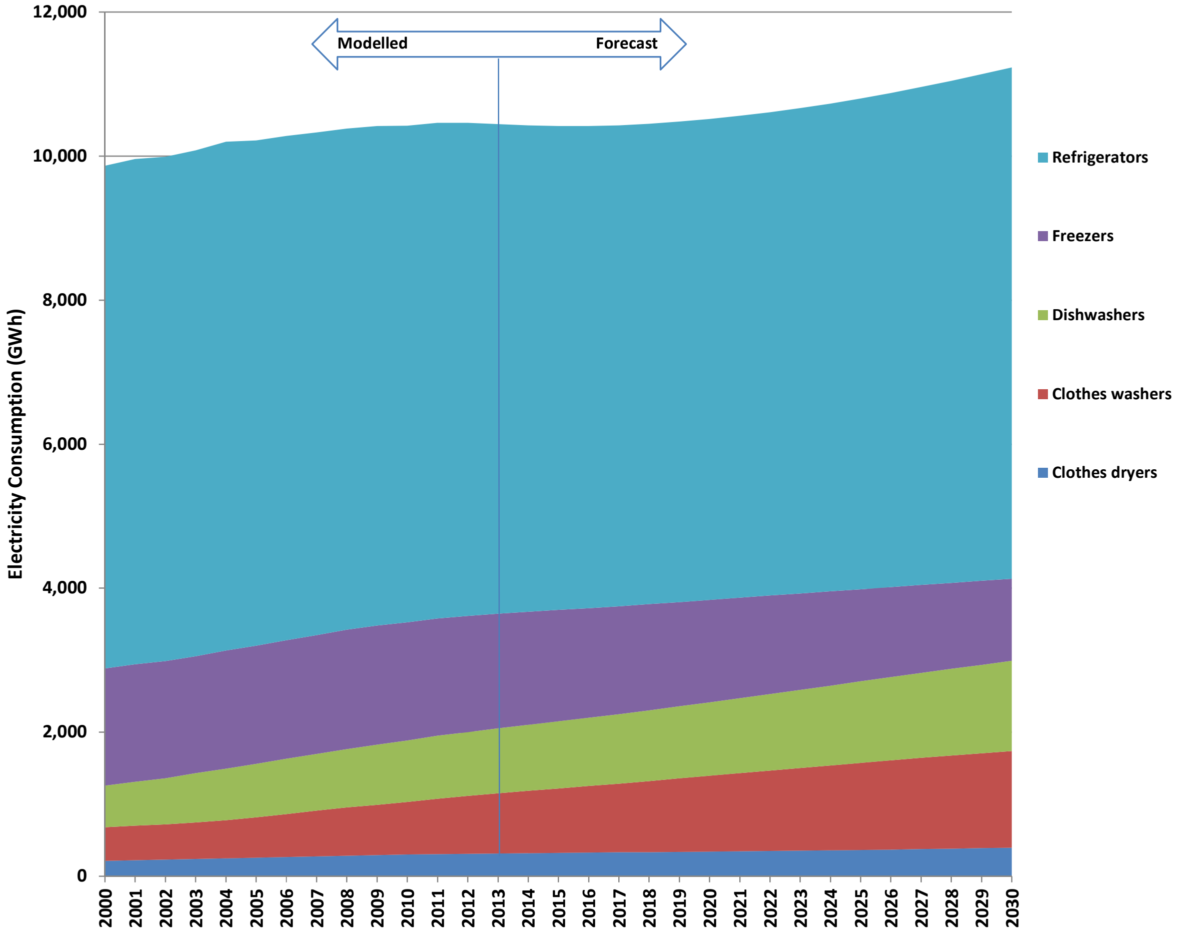

Figure 7: Estimated and forecast electricity consumption of white goods end-use in Australia

Factors contributing to energy use trends

Energy use by white goods has been impacted by a number of factors, some causing decreases in energy and others increasing energy use. Refrigerators and freezers have been subject to MEPS (1999 and 2005) and energy labelling (since 1986, with updated scales in 2000 and 2010). The overall energy use of new refrigerators has declined by over 35% from 1996 to 2005, which has had a significant impact on the total refrigerator energy use, although ownership has increased to almost 1.4 refrigerators per household by 2010. The combined impact of these two factors means that energy use by refrigerators has increased by 7% from 2000 to 2010. Further MEPS are planned; however details are not yet published. The other major factor contributing to the increase in energy use by white goods is the shift from top loading to front loading clothes washers, which uses more energy as they generally heat water to a minimum temperature to enhance washing performance while lowering total water use. Clothes washer energy use has increased by a factor of three from 2000 to 2014. Forecast energy use by white goods shows an increase in energy use over the period 2020 to 2030, as current impacts of MEPS diminish and total energy use increases with the projected increase in the number of households.

Appliances – IT&HE

The total energy use of Information Technology & Home Entertainment (IT&HE) increased by almost 100% from 2000 to 2010. It is then forecast to decline to 2020 and a slow increase to 2030, as shown in Figure 8.

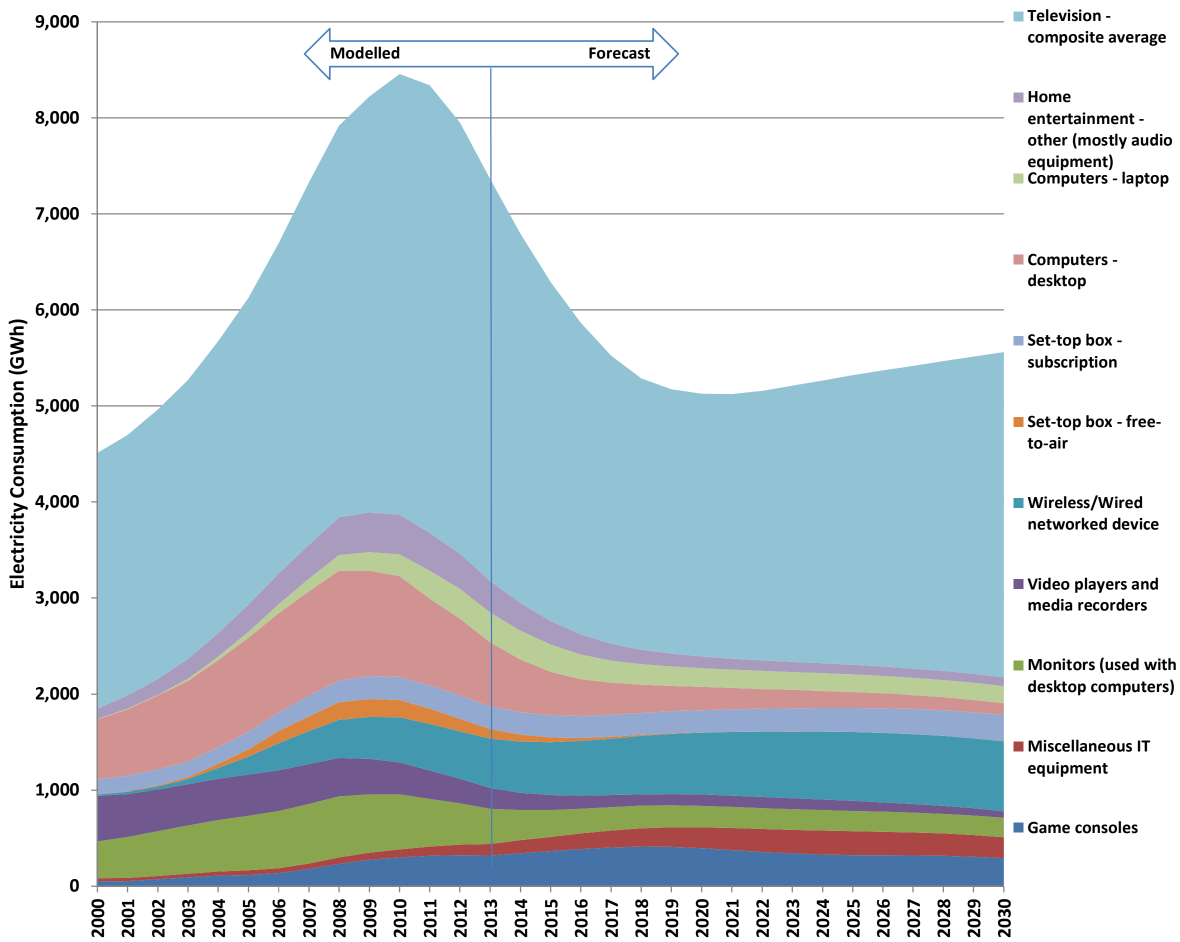

Figure 8: Estimated and forecast electricity consumption of IT&HE end-use in Australia

Factors contributing to energy use trends

The main factor contributing to the rapid increase in IT&HE energy use to 2011 was from the increase in TV ownership (from 1.7 in 200 to 2.2 in 2011) and purchase of larger flat screen TVs. At the same time, energy use of new TVs increased by over 50% from 2000 to 2008. However, due to the technological improvements in the efficiency of new TVs and the introduction of MEPS and labelling in Australia in 2009, the energy use per new TV has now declined to levels below those of the old screen technology used in the last century. Ownership of TVs has also declined to less than 2 per household in 2014 and is forecast to decline further with the change to portable devices for viewing of video by consumers. The forecast increase in energy consumption by TVs from 2020 is due to the increase in average size and number of higher energy consuming TVs, such as ultra-high definition. Another factor reducing energy use is the increased use of laptop/notebook PCs and tablets which has led to the decline in total energy use by desktop PCs in households. Network devices (which are always connected and using power) are forecast to further increase their share of total IT&HE energy consumption as their numbers increase.

Conclusions

Residential electricity use in Australia increased during the 2000s but has declined in recent years since 2008. The modelling reported in this paper explains the major factors contributing to the changes in electricity energy use in the residential sector and explores the impacts of these trends on forecast electricity use. There have been dramatic declines in the last five years in the electricity consumption in some end-uses, such as hot water, IT&HE and lighting, but these have been masked by the increase in energy use of space conditioning and white goods. With continued changes in types of equipment installed in households, and the improvements in efficiency being realised in the stock of equipment, total electricity use is now declining and forecast to continue to decline till 2020.

With increasing population and hence households, total electricity consumption is then forecast to increase from 2020.

The efficiency measures introduced by governments during the period 1999 to 2012 have contributed significantly to the decline in total residential energy use seen in the last few years. The largest regulatory impacts have been from MEPS for heat losses of electric storage hot water heaters, MEPS for lighting, and MEPS and Labelling for TVs, refrigerators/freezer and air conditioners. Significant impacts have also occurred due to state and federal government programs that encouraged the installation of efficient showers, solar/heat pump water heaters and efficient lighting.

Householders switching from electricity to gas fuel for water heating, and the increased use of reverse cycle air conditioners instead of restive heating for space heating, have also had an impact on declining electrical energy use.

The electrical energy use forecast also shows that without further regulated improvements in the efficiency of electric water heaters, refrigeration and TVs in Australia, there is likely to be increasing energy use over the period 2020 to 2030.

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Analysis of the Recent Trends in Residential Energy Consumption in the EU

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Abstract

The EU has adopted targets for an energy consumption reduction of 20% in year 2020 compared to a projected energy consumption in the same year (Business as Usual scenario modelled with Primes in 2007).

The residential sector is responsible for about 26.6% of the final EU energy consumption (the second largest sector after the transport sector). Several policies have been adopted in the EU since the nineties in order to reduce energy consumption in the residential sector, both at EU level (Eco-design, Energy Labelling, Energy Performances of Buildings) and at national level (subsidies, information campaigns, energy supplier obligations, etc.). It is of great importance to understand and explain the energy consumption trends in the residential sector.

The present paper shortly describes the policies adopted, then presents and discusses the most recent trends in energy consumption (mainly focusing on electricity and gas) and other factors that help in understanding energy consumption trends such as GDP, population, number of dwellings, Heating Degree Days and energy prices.

Based on the analysis of the data presented and correlation, conclusions on the impact of adopted policies are presented and discussed as a contribution to better understand the impact of policies and other trends on energy consumption.

Introduction

Energy efficiency has become one of the main policy goals in the European Union. Many important directives and regulations to promote energy efficiency have been implemented or are in the planning phase just before implementation. Furthermore the EU Member States (MSs) have been very active in the area of energy efficiency at the national level, by implemented many policies and measures. The EU 20% energy saving target for 2020 was first introduced by the European Commission (EC) in its Green Paper on "Energy Efficiency or Doing More With Less" of 2005 (EC Green Paper 2005), where it was indicated that this was the cost-effective potential supported by several studies. The 2006 Action Plan (EU EE Action Plan 2005) proposed a set of energy efficiency policies at EU level to reach the 20% energy saving target by 2020. In March 2007, the EU leaders committed themselves to transform Europe in a highly energy-efficient, low carbon economy and agreed on the so-called "20-20-20" targets. This includes three key objectives for 2020:

- a 20% reduction in EU greenhouse gas emissions from 1990 levels;
- raising the share of EU energy consumption produced from renewable resources to 20%;
- an improvement in the EU's energy efficiency to achieve a 20% savings on the EU primary energy consumption (The Conclusions of the European Council of 8 and 9 March 2007).

The targets were set by, and were enacted through, the Climate and Energy Package in 2009. The Climate and Energy Package is a set of binding legislations which aim to ensure that the European Union meets its ambitious climate and energy targets for 2020.

The Energy End-use Efficiency and Energy Services Directive (2006/32/EC, ESD 2006) introduced the indicative energy saving target of 9% over a 9 year period 2008-2016. Each MS had to adopt an indicative target for end-use efficiency of at least 9%. This target has been set and calculated in accordance with the method set out in Annex I to the Directive, i.e. it is based on the average final energy consumption of five past years (2001-2005). The target excludes some end-use sectors, such as the industry sector under ETS. A number of MSs introduced targets for 2016 higher than 9%. It is important to notice that this is a target for final end-use that is expressed in final energy normally, but that could also be expressed in primary energy using a fixed national conversion factor (the European Commission recommended using a factor of 2.5). The target does not include efficiency improvements in the energy supply (e.g. generation), although some renewable energy sources and cogeneration where included.

Another very important measure introduced by the ESD is the National Energy Efficiency Action Plans (NEEAPs). NEEAPs were introduced as a way to present how a MS was introducing (or relaying on existing) new policies and programmes, to reach the 9% ESD energy saving target. At the time of the ESD adoption only a few MSs had the experience to prepare and adopt NEEAPs. Three NEEAPs were foreseen by the ESD, one in 2008, one in 2011 and a final one in 2014. The NEEAP[1] should be a strategic document showing a coherent set of policies and measures needed in a specific MS to reach the 9% target (see also discussion in the next section). In addition, the second and third NEEAP should include the calculation of the energy savings achieved in the past three years (and including early actions when these are allowed).

In order to meet the EU 2020 target and given the somewhat slow progress by MSs in implementing energy efficiency policies to meet the 2020 target, the Commission proposed on 22 June 2011, a new Directive to step up MSs efforts to use energy more efficiently in all sectors including the energy production, transformation and distribution to final consumers. The Energy Efficiency Directive (EED) (EED 2012) was adopted in December 2012. The EED contains several measures, such as: legal obligations to establish energy saving schemes in MSs, public sector to lead by example, energy audits, energy services, efficient CHP, energy efficiency funds, metering, consumer behaviour, etc.

One of the key articles of the EED is Article 7, introducing Energy Efficiency Obligation Schemes (EEOS). Article 7 of the EED requires MSs to achieve a certain quantity of final energy savings in end-use sectors. This is an important element contributing to achieving the overarching 20% target.

Article 7 of the EED requires MSs to establish Energy Efficiency Obligation schemes (EEOs) mandating energy retail energy sales companies or distributors to reach energy savings targets or use alternative policy measures to deliver a targeted amount of energy savings amongst final energy consumers. The energy savings to be achieved by EEOs must be at least equivalent to achieving new savings each year from 1 January 2014 to 31 December 2020 of 1.5% of the annual energy sales to final consumers of all energy distributors or all retail energy sales companies by volume averaged over the previous three consecutive years, where data is available (baseline). Existing EEOs in operation in the UK, France, Italy, Denmark and the Flemish regions of Belgium have promoted efficiency equipment and building insulation in the residential sector.

Another important energy efficiency policy action at EU level has been the introduction of minimum efficiency requirements for products. The Eco-design Directive (Directive 2009/125/EC, EC 2009**)** is the EU framework legislation that allows the introduction of energy efficiency requirements for energy related products such as lamps, residential appliances, consumer electronics, ICT, etc. Since the first Eco-design Directive (Directive 2005/32/EC, EC 2005**)** was introduced a number of implementing Regulations have been adopted introducing efficiency requirements for residential appliances (refrigerators, freezers, washing machines, etc.), lamps, televisions and air-conditioners and most recently heaters and water heaters[2]**.** Efficiency requirements have been complemented by mandatory energy labelling (Directive 2010/30/EU, EC 2010**)** [3]. Energy labelling of residential equipment was first introduced in 1992 (Council Directive 92/75/EEC**), with the first energy label introduced in** 1994 for refrigerators. Energy label has contributed to enlarge the market for efficient appliances (JRC 2012). The combination of Eco-design and energy labelling has been successful in substantially improving energy efficiency of residential equipment and thus result in energy savings compared to a business as usual scenario (Labanca 2013).

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[1] The evaluation of the quality of NEEAPs and the saving reported in not in the scope of the present paper,

[2] For the updated list of the Regulations adopted and the products covered by efficiency requirements under the Eco-design see: https://ec.europa.eu/energy/sites/ener/files/documents/list_of_ecodesign_measures.pdf

[3] For the updated list of the Regulations adopted and the products covered by energy labelling see: https://ec.europa.eu/energy/sites/ener/files/documents/list_of_enegy_labelling_measures.pdf

The main EU policy for buildings is the Energy Performance of Building Directive (EPBD) introduced firstly in 2002 (Directive 2002/91/EC) and then recast in 2010 (Directive 2010/31/EU). Under the Energy Performance of Buildings Directive, MSs have to implement at national level the following measures: energy performance certificates to be included in all advertisements for the sale or rental of buildings; regular inspection of heating and air conditioning systems; all new buildings must be nearly zero energy buildings by 31 December 2020 (public buildings by 31 December 2018); introduce a set of minimum energy performance requirements for new buildings, for the major renovation of buildings and for the replacement or retrofit of building elements (heating and cooling systems, roofs, walls, etc.);. MSs have also to draw up lists of national financial measures to improve the energy efficiency of buildings.

EU Gross and Final Energy Consumption

Gross Inland consumption in EU-28 declined from 1,727 Mtoe in 2000 to 1,686 Mtoe in 2012. Fig. 1 shows how Gross inland consumption and final energy consumption have evolved from 2000 onwards: both energy consumptions have declined in this period. In 2012 final energy consumption in EU-28 for all sectors was 1,104 Mtoe. This energy was consumed by four main sectors (Fig.). The sector with the largest final energy consumption is the transport sector, with a share of 31.8% of the final energy. The residential sector is second, with a share of 26.2% of final energy. Industry is third with a share of 25.6% of the final consumption and last, the share of the service sector is 13.5%. Final energy consumption declined by 2% the period 2000 – 2012. In 2000 it was 1,131 Mtoe and this dropped to 1,104 Mtoe by 2012 (Fig.1). The sub-sectors were there was reduction in final energy consumption compared to 2000 are the residential sector (-2%) and industry sector (-15%). On the contrary, during the same period energy consumption increased in the service sector by +27% and in the transport sector by +2%.

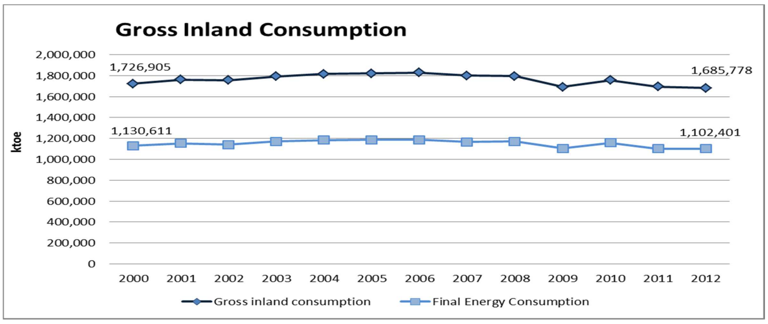

Fig. 1 Gross Inland energy consumption – Final energy consumption, EU-28, Data Eurostat.

The decline of 2.3% in the final energy consumption, for the period 2000-2012, has not been constant. Until 2012, final energy consumption was higher every year compared to 2000, with the exception of the years 2009, 2011 and 2012. From 2003 until 2006 there was a constant growth. The years 2002 and 2007, although final energy consumption was still more than that of 2000, the annual rate of growth was lower, which could be related to the high temperature of these years. Consumption reached a peak on 2006 with 5.2% growth and a minimum on 2012 with a drop of 2.3%, compared to 2000 levels. In EU-15 final energy consumption dropped from 970 Mtoe in 2000 to 935 Mtoe in 2012. This represents a reduction of 3.6%. Final energy consumption in EU-15 reached a peak on 2005 with 1,015 Mtoe which is 4.6% higher than the consumption in 2000. The minimum consumption for this period was in 2012 with a 3.6% decline. In NMS-13 final consumption grew from 161 Mtoe in 2000 to 169 Mtoe in 2012. This equals a growth of 5.4%. In contrast to EU-15, consumption was constantly higher than that of 2000 levels.. The peak point was in 2008 with 178 Mtoe consumed, a 10.5% increase compared to 2000. The main energy fuels of final energy consumption are petroleum products, gas and electricity, which provide respectively the 39%, 22.9% and 21.8% of the final energy consumption in 2012.

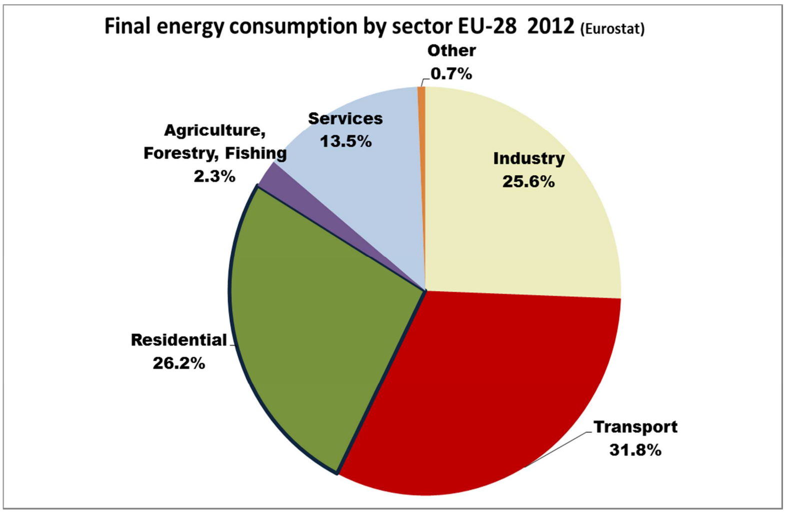

Fig. 2 Final energy consumption – Shares by sector, EU-28, 2012, Data-Eurostat

Residential Energy Consumption

In 2012, residential energy accounted for 26.2% of the final energy consumption (Fig. 2). The energy fuels with the largest share are gas (37.4%) and electricity (24.6%). Renewables account for 14.1% of the energy supply, total petroleum products for 13.2% and derived heat for 7.5%. There have been some changes in the breakdown of energy types since 2000. The share of electricity and renewables has increased by 3.6% and 4.3% respectively. In contrast, gas decreased by 0.9% petroleum products by 6.3%, heat by 0.4% and solid fuels by 0.2%. Because of the importance of gas and electricity, a special focus will be given to these energy fuels for the residential sector.

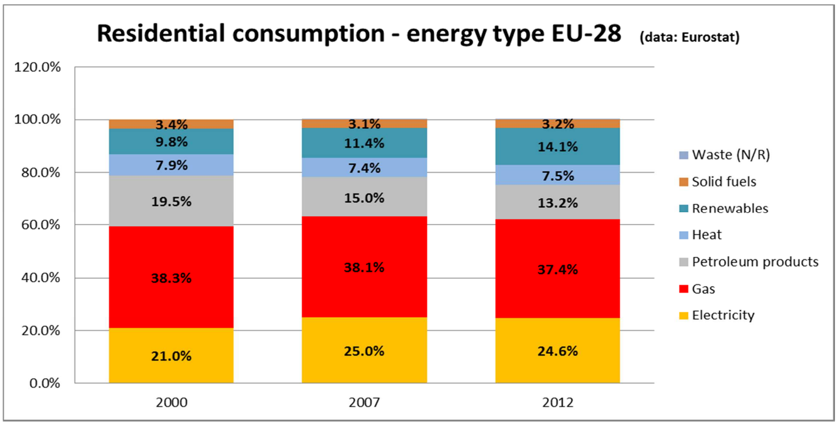

Fig. 3 Shares of energy fuels for residential consumption in EU-28, 2000, 2007, 2012. Data: Eurostat.

In 2000 residential energy consumption in EU-28 was 294 Mtoe (Fig. 4). In 2012 it dropped to 289 Mtoe, a reduction of 1.8%. Residential consumption was higher than the 2000 levels from 2001-2006. After 2007 consumption dropped suddenly. Only in 2010 it was higher than the 2000 levels again, with an increase of 5.7%, which was also the highest point of all the period. This year however there was a very cold winter which could have driven the heating demands up (Fig.). In 2011 there was a sudden drop with consumption being 5.7% less than the 2000 levels. In 2012 it increased slightly again. From a comparison of Fig. 4 and 5, it can be seen how the changes in heating degree days relate to the changes in the residential energy consumption. In 2007 and 2011 there was a mild winter and the residential energy dropped accordingly. In 2010, when there was a very cold winter residential energy consumption went up.

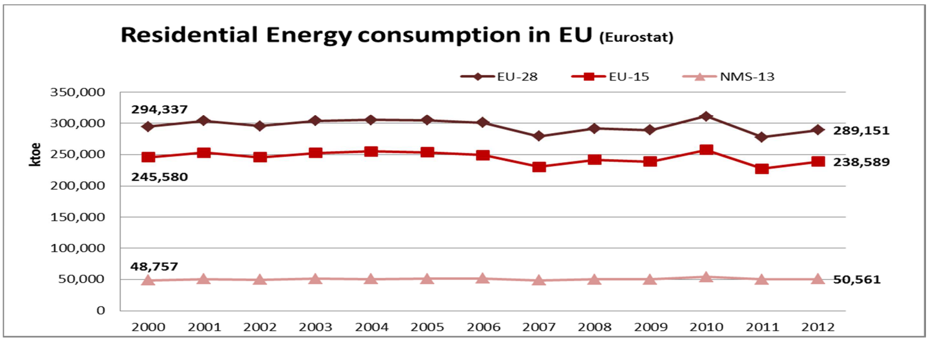

Fig. 4 Residential energy consumption in EU-28, EU-15, NMS-13. 2000-2012. Data: Eurostat

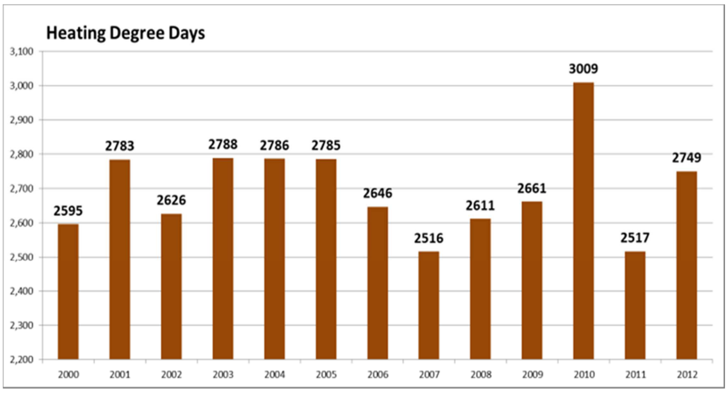

Fig. 5 Heating Degree Days EU-28, 2000-2012, Data: Odyssee

Some demographic developments

When analysing energy consumption trends it is important to consider other factors influencing energy consumption such as economic development, weather conditions, equipment penetration and usage trends and population. No quantitative econometric analysis aiming to assess the influence of these factors is presented in this paper (Bertoldi, Hirl,). Nevertheless, possible explanations for consumption patterns can be identified by comparing energy consumption with the trends observed for some of these factors. In the following section, the trends of the following parameters will be considered: population, GDP per capita, weather conditions (actual heating degree days), number of dwellings per country, average persons per household. This analysis can in principle help to better understand the relation between energy consumption and efficiency trends[4] in the residential sector. For instance, a decrease of total energy consumption could be explained by a decreasing population and not by a more efficient use of energy.

Population

Between 2000 and 2012 population in the EU-28 grew by 3.62%. In the same period residential energy consumption fell by 1.8% but residential energy consumption per capita fell even more, by 5.19 (fig.6)

[4] The paper does not aim to attribute efficiency trends to technological development or to policies. However a share of the efficiency progress is due to adopted policies.

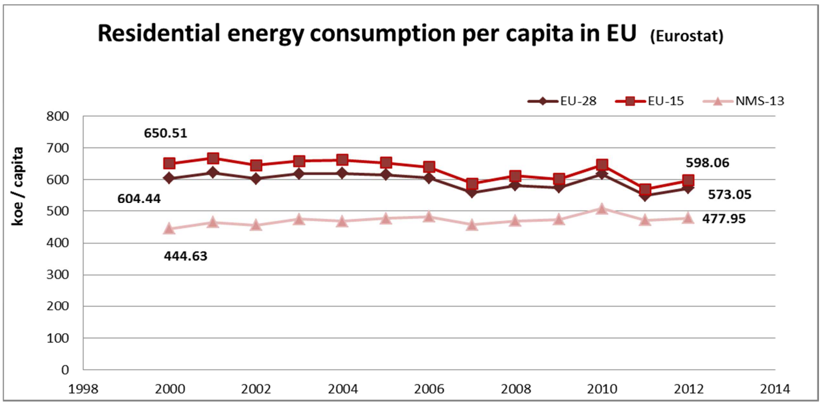

Fig. 6 Residential energy consumption per capita, EU-28, EU-15, NMS-13 for 2000-2012. Data: Eurostat

Because of the interdependence of the HDD with the residential energy consumption, it is interesting to see how the residential energy has evolved normalized by the HDD. In EU-28 there is a decline between the years 2000-2012. This decline has happened mostly in the EU-15 where with the exception of 2011, there was a gradual downward movement after 2006. In NMS-13 the situation looks very different, as there was a decline between 2008 and 2010, but after 2010 there is growth. Overall in EU-15 there has been large decline while in NMS-13 there has been a slight growth of this indicator. Fig. 7 shows this evolution for individual MS. Most of the NMS-13 rank very low on this indicator. That could explain their growth the last years. Cyprus and Malta are an exception probably due to the small number of HDD[5].

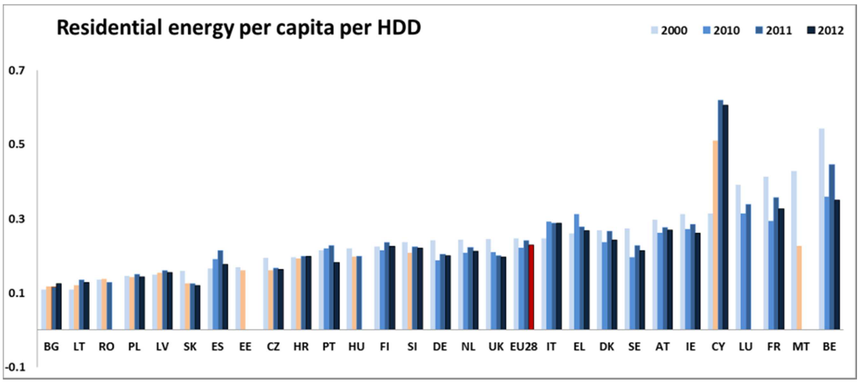

Fig. 7 Residential Energy per capita for Member States, 2000,2005,2010,2012 Data: Eurostat.

Gross Domestic Product (GDP)

Another factor that influences energy consumption is the economic development and economic situation of the MS. GDP per capita has been increasing during 2000-2012, with a drop in GDP in 2009 due to the economic and financial crisis (Fig. 8). After 2009, GDP per capita increased again. In 2011, GDP reached again similar levels as those of 2008, i.e. before the crisis.

[5] Most probably this is also due to the high number of Cooling Degree Days, which are not included in the present analysis.

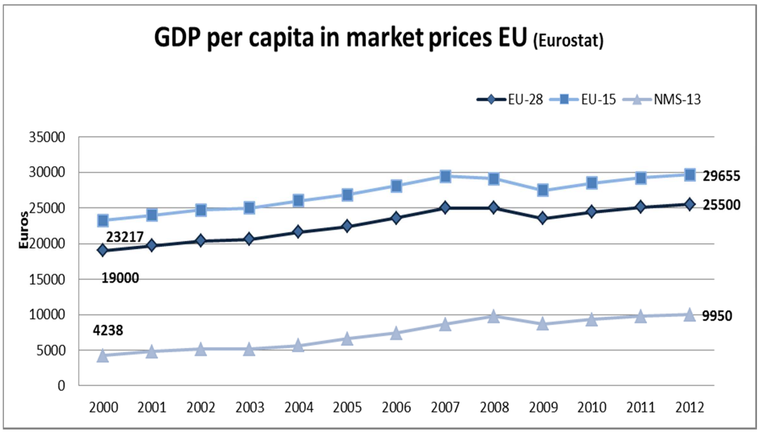

Fig. 8 GDP per capita in market prices, EU-28, EU-15, NMS-13, 2000-2012. Data: Eurostat

The growth in GDP per capita is connected to economic development during these years which can affect energy consumption in multiple ways. It can result in increase of residential energy consumption, by increase of comfort levels, but it can also be accompanied by more efficient ways of energy usage. In the household sector, increase in efficiency is mainly due to more efficient appliances and equipment, more efficient heating systems and better insulated buildings, most of which require large initial investments.

Therefore by comparing economic growth and energy consumption it can be observed that there is some small correlation. In EU-15 where GDP grew less, there was reduction of residential energy consumption. Fig. 9 shows the GDP per capita for different MSs and for different years. It can be seen that besides the high rate of growth in many MSs, the actual GDP in these MSs is still much lower than the EU-average GDP per capita. Therefore GDP growth in MSs with below average GDP could have led to more consumption of residential energy due to increasing comfort levels. On the contrary, in EU-15 with a high level of GDP per capita being already achieved it is possible that GDP growth, instead of being used directly for additional energy consumption was partly invested for more energy efficient equipment or building insulation.

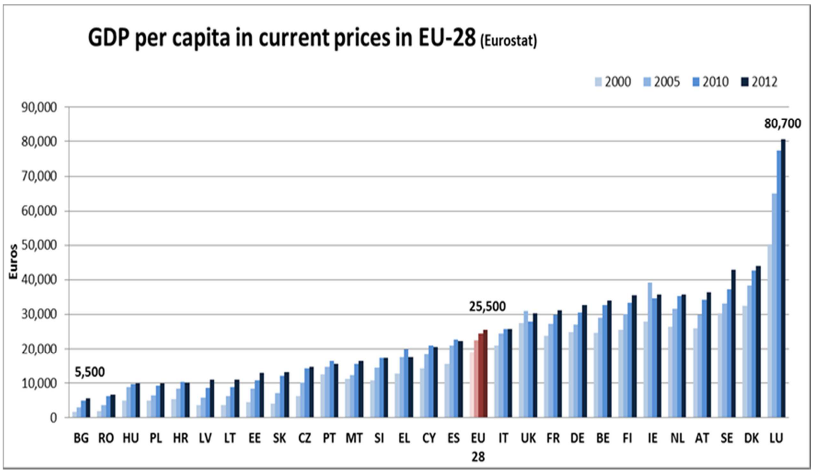

Fig. 9 GDP per capita for different Member States. 2000,2005,2010,2012 Data: Eurostat.

There is large diversity in the GDP per capita across MSs. Given the large dispersion, it is of interest to see average energy consumption figures for each of the Member States. Data related to final residential energy consumption per capita in the year 2012 indicate that Finland has the highest consumption per capita and Malta the lowest. In Finland there is high demand for heating and the use of saunas is very widespread. Malta on the other side has one very low heating degree days. Other MSs that have very low consumption per capita: are Portugal, Spain and Cyprus all of them have warm climates. However Romania and Slovakia, which have also very low residential energy consumption, have medium HDD. The MSs with the highest consumption per capita (Finland, Luxembourg, Denmark, Sweden, Austria), have also above average GDP per capita. Higher GDP levels may indeed lead to buy more energy-using equipment or to larger dwellings resulting hence in higher energy consumption. But as already mentioned above, economic growth can also lead to more energy efficient equipment and buildings resulting in lower energy consumption levels. An indication of this is that the MSs with the highest GDP per capita (Luxembourg, Denmark, Sweden, Austria) have not experienced significant growth in the residential energy per capita compared to 2000. Although per capita residential consumption in EU-28 has decreased slightly since 2000, when looking in details at the different MSs, there have been significant changes in consumption. Finland, Latvia and Estonia are MSs with large per capita residential energy where energy consumption rose further from 2000 to 2012. In contrast, in Belgium and Luxembourg there has been significant decline.

Fig. 10 shows more information about the different MSs. With the exception of Cyprus there has been decline on all other MSs. The lowest values are in Luxembourg, Denmark and Finland all of which are MSs with large GDP and HDD.

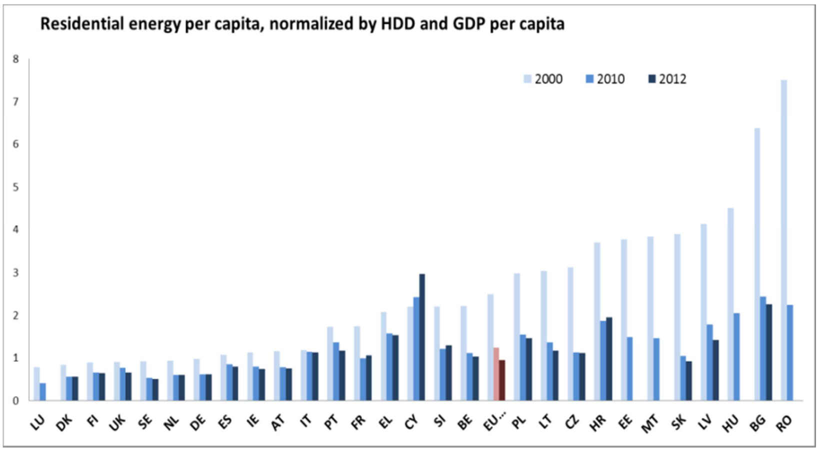

Fig. 10 Residential energy per capita, normalized by HDD and GDP per capita for Member States Data Eurostat, Odyssee

Household and Dwelling size

Residential consumption is also influenced by other factors, such as the dwelling and the household size[6]. The average household size in 2012, in EU-28, was 2.3 persons per household. Single and small households have an higher per capita energy consumption than large family households. Most energy- using equipment is shared by the people living together in one household, especially heating and cooling, white appliances and also most electronic equipment. Sweden had the lowest average number of people per household (1.9) and Romania the highest (2.9). The overall development in Europe is an increase in the number of smaller households which leads to an increase of energy consumption per household. Dwelling size, measured in m^2 is another important aspect. Larger dwellings generally have a higher heating and cooling demand and possibly higher energy consumption by lighting equipment. Romania has the smallest dwelling size besides being the country with the maximum people per household. Latvia, Lithuania and Poland have also small dwelling size. MSs with large dwellings are Cyprus, Luxembourg, Ireland, Denmark and Netherlands. These MSs, with the exception of Cyprus, have higher than average residential consumption per capita. In almost all MSs, there is a gradual increase of the floor area of dwellings which could lead to an increase of heating demand.. Malta, Bulgaria and Portugal have very low consumption per dwelling, while Finland, Denmark, UK and Austria have very high consumption per dwelling. Most of the MSs, that have large dwellings, have also larger than average energy consumption per dwelling. However there are MSs such as Cyprus, Italy, Spain and Portugal, that besides the large dwelling size, have less than the average consumption. This could be related to differences in heating degree days or per capita GDP. The average final residential energy consumption per dwelling in the EU[7], in 2012, was

[6] A household is a group of persons who share the same living accommodation and who consume certain types of goods and services collectively, mainly housing and food

[7] Dwelling data were available for 20 MSs

1.14 toe/dw and in 2000 it was 1.21 toe/dw, a decline of 5.8%. In contrast, average dwelling size has increased by 3.9%.

Residential consumption per dwelling varies over time, however it can be seen Fig. 11 that the values are lower after 2007 compared to those before. An exception is in 2010 when it rose to 1.25 toe/dw, which is similar to the value in 2006. In 2011 it dropped again reaching the minimum for the period after 2001. These variations are similar to the variations in the heating degree days. In 2007 there was a drop in heating degree days and on 2010 the peak for the period. However it can be seen that the decrease in consumption per dwelling, is higher than what could be explained by the heating degree days alone. For instance in 2009 the heating degree days were higher than those of 2006 and 2002, but consumption did not reach again the levels of those years. Also in 2010, HDD reached the maximum of the period 2000-2012, while the residential energy per dwelling only reached the levels of 2006. Last in 2011, HDD increased again at higher values than 2007-2008, but dwelling consumption dropped to the minimum of the period 2001-2011.

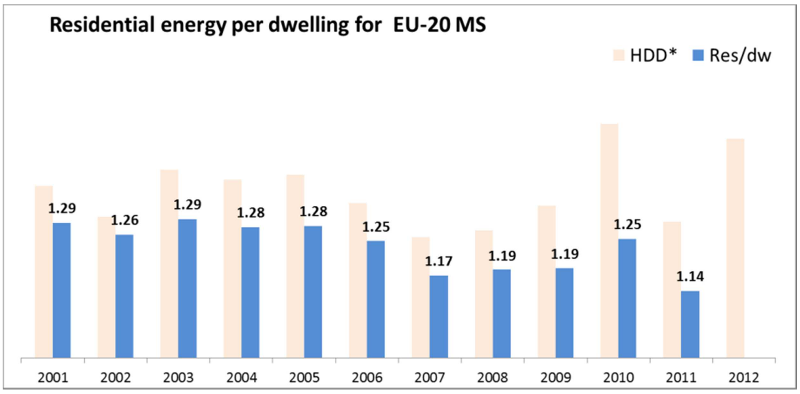

Fig. 11 Residential energy per dwelling in EU-20*[8] comparison with HDD[9], 2001-2011. Data Eurostat, Odyssee

Due to the differences in average dwelling sizes between MSs, it is also interesting to see how the energy consumption varies over the floor area. Portugal, Cyprus and Spain have the lowest residential energy per floor area, while Romania, Finland and Latvia have the highest values. Romania has one of the smallest floor areas and that could explain why it ranks very high. When looking at the residential consumption per floor area compared to HDD, the changes follow very similar patterns to the changes of the residential consumption per dwellings. By using the dwelling size for each different MSs, it is possible to correct the residential energy per dwelling and HDD for differences in average dwelling size between different MSs. Fig. shows the residential energy per square meter and per HDD, while Fig. 13 shows the same for different MSs. In half of the MSs (nine out of the eighteen), there has been a decline in 2011 compared to 2001. Six of the MSs with the decline belong to new MSs. By calculating the average of these MSs from 2001-2011 it can be seen that overall there is a decline.

[8] Only MSs with complete data for all the years were taken into consideration. It excludes AT, CZ,EE, FR, HU,IE,LU,MT

[9] HDD have been divided by 2000 for comparison.

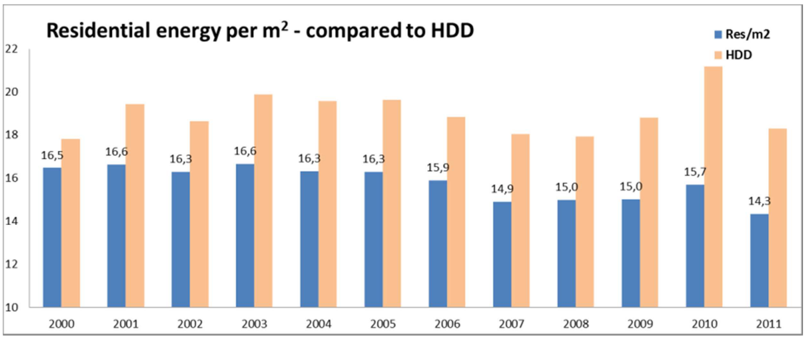

Fig 12 Residential energy per square meter in EU-18[10] comparison with HDD[11], 2001-2011. Data Eurostat, Odyssee

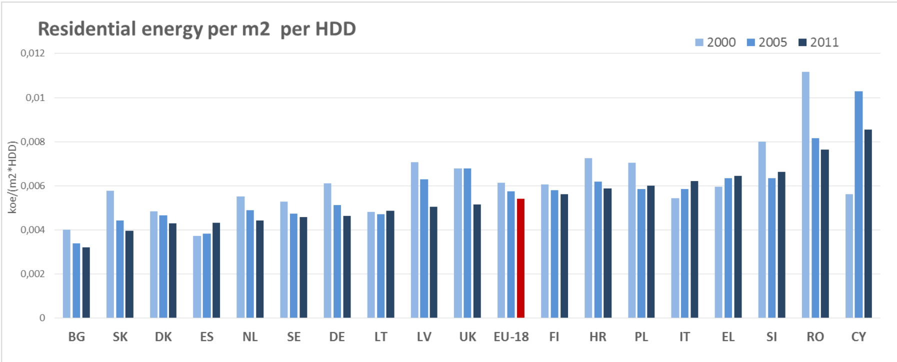

Fig. 13 Residential energy per m2 normalized by HDD for 18 MSs. Data: Eurostat, Odyssee

Fig. shows the residential energy per capita normalized by HDD, GDP per capita and square meter per capita for 18 MSs. By measuring the residential energy on this way, it emerges that there is an annual improvement on energy efficiency from 2000 onwards. Fig. 15 shows the differences between MSs. The largest changes have happened in MSs that belong to NMS-13 while some MSs such as Finland, Denmark and Germany rank very low and there has not been as much change from 2000.

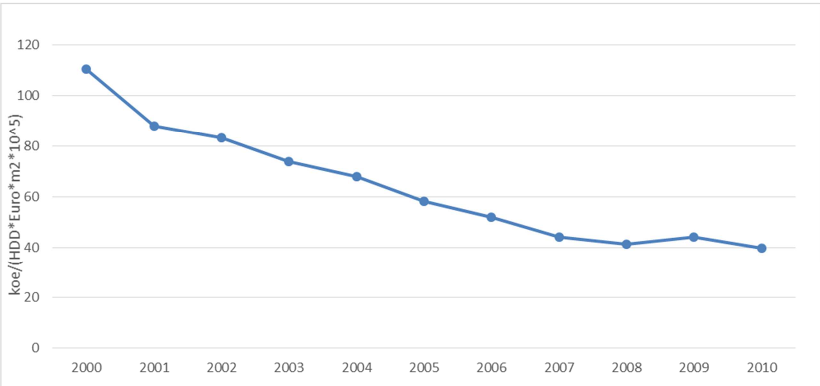

Fig.14 Residential energy per capita, normalized by HDD, GDP per capita, m2 per capita for 19 member states 2000-2010 Data: Eurostat, Odyssee

[10] Only member states with complete data for all the years were taken into consideration. It excludes AT, CZ,EE, FR, HU,IE,LU,MT

[11] HDD have been divided by 2000 for comparison.

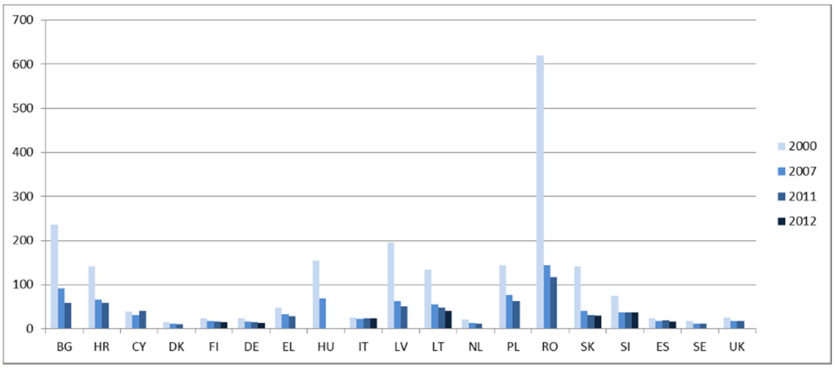

Fig. 15 Residential energy per capita, normalized by HDD, GDP per capita, m2 per capita for 19 MSs. Data: Eurostat, Odyssee

Residential Energy Consumption - Gas

The residential sector is the main end-use sector for the gas consumption 42.8%. Gas consumption is closely related to heating and hot water demand. Besides the residential sector, gas is widely used in industry (35.4%) and less used in the service sector (18.1%). In 2000, final gas consumption in EU-28, was 268 Mtoe and by 2012 it fell to 253 Mtoe, which is -5.5% decline.

In the residential sector, gas has undergone a decline of -4%, from 113 Mtoe in 2000 to 108 Mtoe in 2012 (Fig.). During the years 2000-2002 consumption was stable. From 2003 there was an increase with a peak on 2004. Then there was a gradual decline with a minimum in 2007. After that there were some variations until 2010, when there was a sudden increase of 10.7% compared to the year before. In 2011 there was a sudden decline and consumption reached a minimum for this period of 101 Mtoe. In 2012 consumption increased as well. More specific, in EU-15 consumption changed by -4.6% during 2000-2012, while in NMS-13 there was a total growth of 0.4%, from 12,664 to 12,714 ktoe..

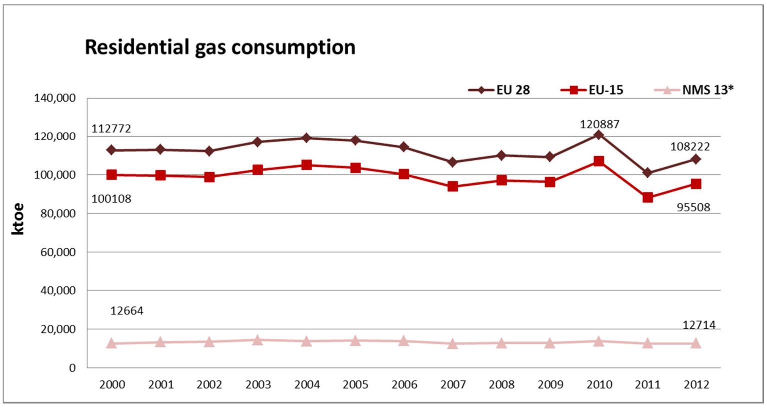

Fig. 16 Residential gas consumption in EU-28, EU-15, NMS-13, Data: Eurostat

The residential gas consumption per capita changed by -7.4% for the period 2000-2012. The breakdown shows that in EU-15 the decline reached -9.7% while in NMS-13 there was a 4.1% growth, compared to the respective consumptions in 2000. The highest consumption in EU-15 was in 2004 and the minimum in 2011 where there was a -16.5% decline. In NMS-13 the highest consumption was in 2003 with 15.7% growth and the minimum in 2007 where the growth was only 1.3% compared to 2000. Fig. 7 shows the residential gas consumption per capita divided by the number of heating degree days for each year. Therefore it gives information on how much gas an individual used on average by correcting for the variations in consumption that are directly related to changes in the HDD. From 2000-2006 there are some annual variations but in total it seems that there are no significant changes. However, from 2006 to 2012, there is a gradual decline. In total the figure has changed by -12.5% since 2000 and by -10.3% since 2006. This shows that there is a gradual reduction in the residential gas consumption that is not directly related or affected by HDD.

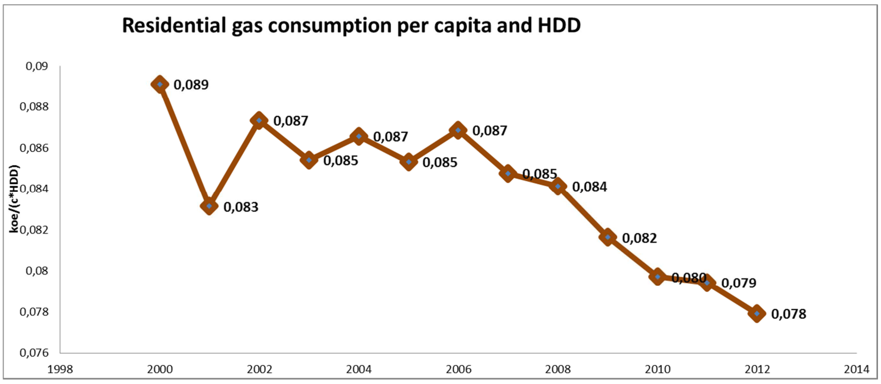

Fig. 17 Residential gas consumption per capita, divided by HDD, EU-28. Data: Eurostat and Odyssee.

The correlation between gas consumption and HDD is also visible in the residential gas consumption per dwelling. In 2001 the average residential gas consumption per dwelling in EU was 0.355 toe. Since then, gas consumption per dwelling on average is decreasing. In 2007 consumption had declined by 12.3% compared to 2001. In 2010 consumption grew again to reach similar levels with those of 2000. From 2001-2011 the minimum value was for 2011 with a total reduction of 15.6%. Overall, the trend in residential gas consumption per dwelling after 2006 is decreasing.

For the residential gas consumption per dwelling and per heating degree days, Netherlands and UK have the highest gas consumption per dwelling, followed by Belgium and Italy (18). In Netherlands and Belgium and Italy there has been growth of the residential gas consumption. In Italy this is related to decline of oil consumption in favour of gas and renewable energies. In the UK there is a decline in residential gas consumption as well as residential gas consumption per dwelling; this is also the case for Belgium, the Netherlands, and Germany. This is an additional indication of the success of the energy policies for reducing heating demand that have been implemented the last years in the UK (EYRE). Very low consumption levels per dwelling can be found in Bulgaria, Greece and Sweden, which do not use gas for heating purposes. Finland, Poland, and Slovenia have big district heating systems for buildings which drive gas consumption level per dwelling down.

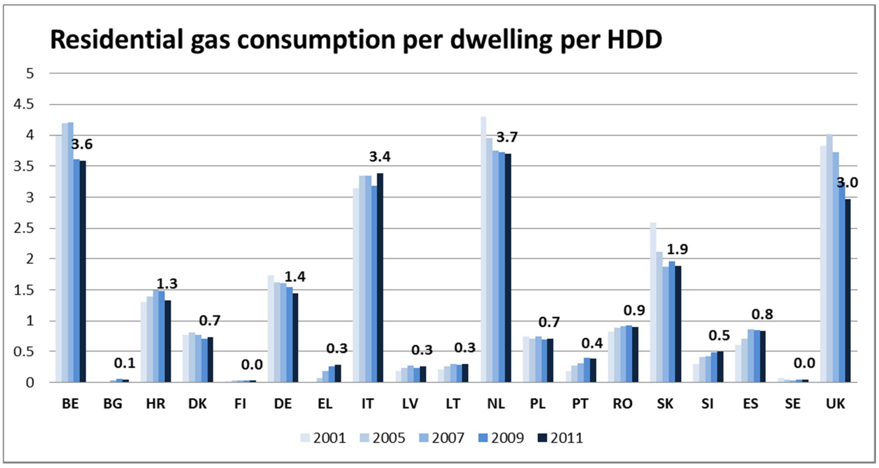

Fig. 18 Residential gas per dwelling per heating degree days, for different member states. Data: Eurostat, Odyssee

Gas prices have been relatively stable from 2007-2010. After 2010 they have increased, with the EU-28 average at 0,07 Euro/kWh in 2012. Sweden (0, 1268 Euro/kWh), Denmark and Italy had some of the highest gas prices in 2012, while Croatia (0,0472 Euro/kWh), Slovakia and Hungary have some of the lowest prices in EU-28. Gas consumption is inelastic to price (Bianco) and consumption is more affected by disposable income than price (Romero-Jordán).

Residential Energy Consumption - Electricity

Final Electricity Consumption was 2531 TWh in 2000 and increased to 2798 TWh by 2012. That is an increase of 10.6%. In 2012, the residential sector used 30.2% of the total final electricity consumption, industry used 36% and the tertiary sector 29.6%. In the residential sector the share of electricity over other energy sources, has become more important as it grew from 21% in 2000 to 24.6% in 2012. Electricity consumption is related to household appliances, consumer electronics, ICT, lighting, water heating, equipment and there are efforts to promote energy efficiency in the sector.

Residential electricity consumption grew by 15% from 720 TWh in 2000 to 828 TWh in 2012 (fig. 19). While final electricity consumption dropped in 2009 and 2011, residential electricity dropped slightly in 2007. In 2007 the annual decline was only -1% while in 2011 was -5%. Both reductions can be related to the low heating degree days as approximately 19% of residential electricity is used for heating systems and electric boilers. Heating degree days had annual drops of 5% in 2007 and by 19% in 2011. In EU-15 the total growth was 14.2% while in NMS-13 growth was 21.3%.

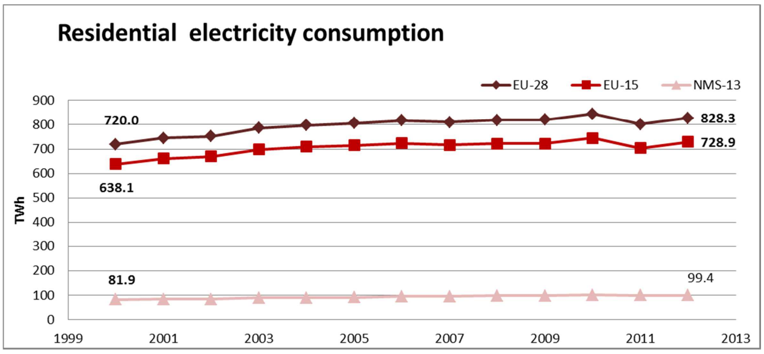

Fig. 19 Residential electricity consumption 2000-2012 Data:Eurostat

Residential electricity consumption per capita has changed from 1479 Kwh/capita in 2000 to 1642 Kwh/capita in 2012 which is an increase of 11%. In EU-15 the change was 8.1% growth while in NMS-13 growth was 25.8% In NMS-13 per capita residential electricity is 940 kWh which is almost half from 1837kWh in EU-15 (fig. 20).

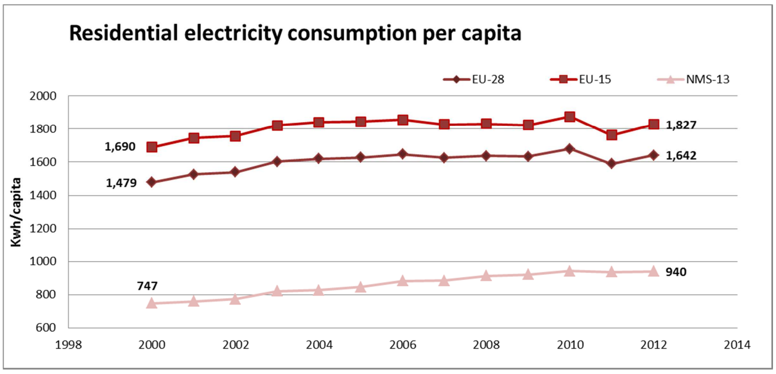

Fig. 20 per capita residential electricity consumption, 2000-2012 in EU-28, EU-15, NMS-13.. Data: Eurostat

Residential electricity consumption per dwelling dropped by 0.6% from 2001-2011. From 2001 to 2005 it grew by 5.6 % from 3.35 to 3.54 MWh/dw. From 2007 it started to decline.

Looking at electricity consumption per dwelling across EU MSs there is a large dispersion of consumption levels. Finland and Sweden have the highest residential electricity consumption per dwelling (Fig.). In Finland besides a high HDD value, there is widespread use of saunas which can be found in many households. In Sweden, there is also very high residential consumption per dwelling, but heating degree days are lower than those of Poland and Germany, which have a lower residential electricity consumption. This could be explained by the use of different heating methods such as heat pumps in Sweden. In addition, in MSs with high electricity consumption levels such as, Finland, Sweden, UK, there seems to be a reduction of consumption in time, while in MSs with the lowest levels (Latvia, Lithuania, Poland Romania) consumption has increased. However it is important to note that the HDD are different as well for each MS. For the above mentioned MSs with the highest and lowest residential electricity consumption, HDD have declined. However for some MSs like Cyprus, Bulgaria and Italy, HDD did not decline or even slightly increased from 2001-2011 and residential electricity has increased as well. It is important to note that consumption per dwelling does not show the consumption pattern of a typical dwelling but it includes a wide variety of very different dwellings and household characteristics. The average includes very small or large dwellings, households as well as low income and high income households etc. For Finland the highest consumption was in 2007 while the higher HDD were in 2009. For Sweden however the changes in the residential electricity per dwelling seem to follow better the changes in HDD.

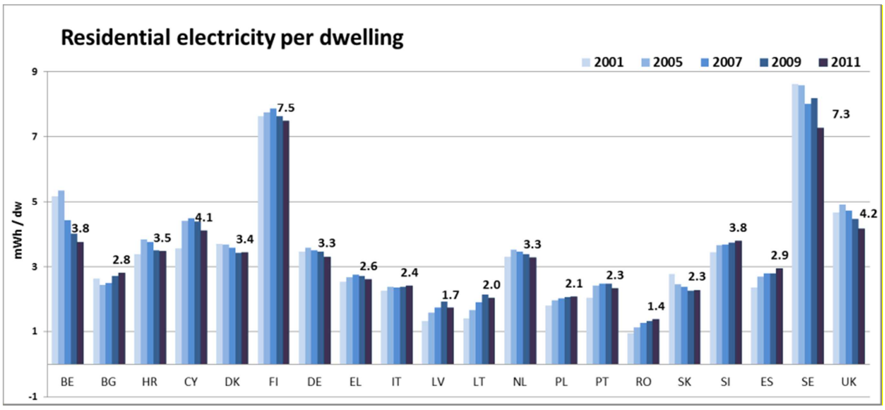

Fig. 21 Residential electricity per dwelling for different member states, Data: Eurostat, Odyssee

There seems to be a growth from 2001-2011for average residential electricity per dwelling and per HDD for 19 MSs. In eleven MSs there has been growth. There was a decline for Bulgaria, Italy, Slovenia and UK. For Finland, Denmark, Cyprus and Hungary the value for 2001 is almost similar to the one for 2011. In contrast to the residential electricity per dwelling and HDD which has grown, the average residential electricity per capita, HDD and square meter has declined. Cyprus has the largest value. When looking into the other MSs, it can be seen that there is very large variation. As shown by fig. 22 the average residential electricity per capita, HDD and square meter has declined.

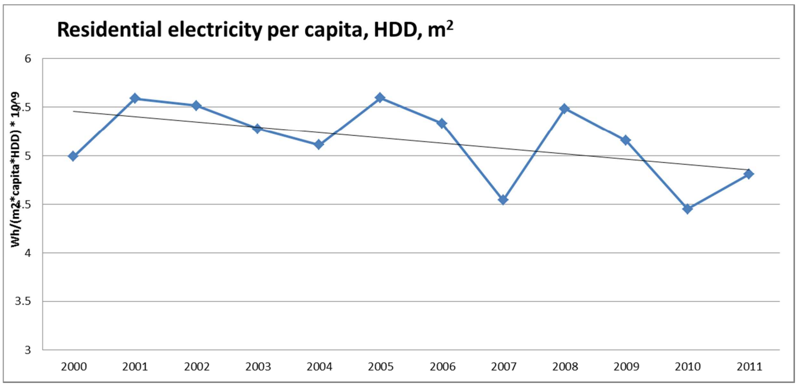

Fig. 22 Residential electricity per capita, HDD and m^2 Data: Odyssee, Eurostat.

Electricity prices differ to a large extent across the European Union. Denmark, Cyprus and Germany have relatively high electricity prices, e.g. 0.29845 € per kWh electricity in Denmark for 2012. Bulgaria and Romania and Estonia have comparatively low electricity prices with the lowest 0.09005 € per kWh in Bulgaria. During the last years, electricity prices have increased in the EU-28. From an average price of 0.1562 € per kWh electricity in 2007 the price increased to 0.1917 € per kWh electricity in 2012. This means an increase of 22.7% during this period. The influence of the price of electricity consumption is, however, not that large since electricity demand is generally quite inelastic (Romero-Jordán).

Discussion and Conclusions

Residential energy consumption has slightly declined in 2012 compared to 2000, by 2%. The changes in the consumption can be described by two main periods. First from 2001-2006 residential energy is constantly higher compared to 2000, while after 2007 the residential energy consumption was lower than that of 2000. The only exception is 2010 when residential energy consumption grew significantly but that was also the year when heating degree days hit the highest point for 2000-2012.

Residential energy consumption is related to heating degree days, because heating demand is the main energy driver of the residential sector. Therefore the annual changes follow a similar pattern both in residential energy consumption and in HDD, which have been also lower after 2007. However on years 2008, 2009 and 2012, the heating degree days were high enough and could have led to more residential energy consumption than the one observed. Energy efficiency improvements or the effects of economic crisis could explain these lower levels of final residential energy consumption.

Other changes that could affect residential energy consumption are population, GDP, number of people per household, dwelling size, size and usage of appliances and saturation levels.. Population has increased [12] (+4%) while the average number of people per household has declined (-8% for 2005-2012). Both of these changes would lead to additional residential energy consumption. Average dwelling size has increased (+3.9%) and larger dwellings require more energy for heating. Last, GDP per capita has increased significantly in all of the MSs. Although the interaction of GDP with the energy consumption is not always straightforward, there are indications that in MSs with low GDP, GDP growth often leads to increase of residential energy consumption. In contrast in MSs with high GDP, further growth is not always accompanied with additional consumption growth.

More than half of the energy requirements for residential energy consumption come from electricity and gas, with gas being the largest energy source for the residential sector. Compared to 2000, the consumption of gas has declined mainly due to more efficient buildings and heating systems. Residential gas consumption dropped by -4%[13].. The decline is residential gas consumption is translated also as a decline in the residential gas consumption per capita (-7.4%) and residential gas per dwelling[14] (-15.6% for 2001-2011). Gas consumption per capita divided by the average heating degree days, shows that after 2006 there is a very constant decline. In the UK and Belgium this trend is quite big and could be placed in relation to energy efficiency policies.

In contrast to gas consumption, the residential electricity per capita grew by +11%.Residential electricity per dwelling[14] dropped by 0.6% for 2001-2011, but this is probably related to very low heating degree days on 2011. For the period 2000-2012, final and residential electricity consumption (but also final and residential electricity consumption per capita), have been every year higher than the consumption of 2000. However, when looking into the annual changes, there have been some years (2007, 2011) when there was decline of the residential electricity consumption. Residential electricity per capita, HDD and m2 has declined slightly over the period indicating that more efficient equipment could have mitigated the impact of larger and more equipment (ICT) and more use of it.

It is important to add that there are very large variations among MSs. When separating the results into NMS-13 and EU-15, it becomes obvious that in NMS-13 total residential energy consumption has not declined at all from 2000, residential gas consumption dropped only in 2007 below the levels of 2000 while electricity consumption has been always higher than that of 2000. However it is important to note that only a 17% of the final residential consumption in EU-28 is consumed in NMS-13 which includes the 20% of the EU-28 population. Also there has been very large GDP/capita growth in NMS-

[12] Unless stated, changes refer to 2000-2012

[13] There is a substitution effect between gas and electricity that is difficult to measure. Gas and electricity could substitute for cooking, water heating, and dishwashing. In principle there is also a substitution for heating by using heatpumps. Finally gas consumption could also decrease by expanding district heating networks.

[14] Dwelling data refer to 2001-2011

13 which can be connected to the increase of energy consumption. Last it is important to note that HDD are higher in NMS-13 compared to EU-15, which could suggest that residential energy consumption will increase further in the future until the same levels of comfort will be achieved.

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Recognizing Appliances and their Events with the same NIALM Algorithm

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Abstract

People are willing to save energy yet most have little to no understanding about the energy consumption of their household devices. Non-intrusive appliance load monitoring (NIALM) is an approach to automatically measure a household's energy consumption and identify switched-on appliances. This paper presents our ongoing research on improving electric load recognition thus helping people to better understand their energy consumption.

A BFTree detects events and classifies devices using features extracted with a Fourier Transformation. Combining detection and classification into one algorithm is achieved by introducing the concept of "noise". Our novel approach detects events with 93% accuracy and correctly classifies 88% of the switched on devices.

Keywords—NIALM; NILM; load disaggregation; event detection; device categorization; device labelling; device recognition; machine learning algorithm; BFTree; intelligent environment; Fourier Transform

Introduction

While low power consumption of electrical devices is of growing importance for users and manufactures resulting in more power efficient devices, the overall consumption is growing. In Switzerland, one reason for the increasing consumption is the growing population. Another reason is the raising number of electrical household appliances. The Swiss government published different strategies describing how the total energy consumption can be decreased in homes [1], e.g.:

a) Substitution of devices with more efficient replacements
b) Automatic switch off of unused devices
c) Visualization of energy consumption to give users a better understanding of their energy consumption

It is getting more and more difficult to identify household devices that significantly contribute to the energy consumption. New devices have many device states (e.g. a blender can have different spin levels influencing its energy consumption) and it is not straight forward to know the associated energy consumption. In addition, most users have little to no understanding about their energy consumption although they are willing to save energy.

Non-intrusive appliance load monitoring (NIALM) is one approach to face these challenges: Based on low cost measurement systems or smart meter values, NIALM automatically detects and classifies switched-on appliances. Thus, NIALM automatically assess how much energy each appliance consumes and opens new possibilities to save energy by better informing the user: Inefficient devices can be easily identified, even automatically switched off, and real time information on consumption can be provided to users to increase their energy awareness at home.

Current NIALM approaches typically use a two-step approach: first, device state changes such as switch-on or switch-off events are detected without considering the individual device characteristics. If an event is detected, a second algorithm recognizes the device class that caused the change based on previously trained characteristics. These two steps are performed with independent algorithms. In some cases, the classification algorithm will classify incorrectly detected events to known classes. A common source of such events is strong noise as typically generated by switched mode power supplies. The second algorithm must classify these incorrect events to known device classes, although no similar reference devices are trained. This NIALM approach therefore suffers from error propagation through the two steps. In this paper we present an approach to combine the two algorithms while still using an event-based approach. Without setting a single threshold, events are detected correctly in 93% of all cases and in 88%, the true class has been chosen by the classification algorithm.

Related work

The first NIALM system was proposed by Hart [2] more than 20 years ago. A good overview on NIALM research was compiled by Liang [3], [4]. Liang explains that the main challenge in NIALM is to reliably detect different working states of electrical devices in order to maximize the device recognition performance. Our approach builds on Mathis et al.'s work [5] on labelling device states to categories to maximize recognition accuracy.

Recently, Parson presented a new NIALM approach [6], which also uses a single algorithm for device recognition. For his algorithm evaluation, he compared different private and public datasets and looked at different disaggregation algorithms to detect individual devices in a household. He disaggregated the devices in 10s intervals with a Hidden Markov Model. One of the main differences to our work is the sampling rate of the measurements. We use a micro level approach while Parson uses a macro level one. Micro level means that the sampling rate is higher than the fundamental waveform of the AC signal, whereas the macro level approach's sampling rate is lower. While smart meters measure internally in micro level, they often only provide macro level data. Another difference is that Parson does not implement an event based approach.

An often used approach for system validation is using dedicated sub-meters at device level to provide the true switching event of each device. The NIALM algorithm can then be validated on this data. Kolter published such data [7]. As some of these sub-meters still contain more than one device, an evaluation tool has been developed for our application, on which we validate our system. In further work our system will get validated on public data such as from Kolter.

Methods

The developed NIALM framework (see Figure 1) is described in the following paragraphs. Our method works with a single algorithm for event detection and classification and is integrated into the NIALM framework of [5]. This section describes data acquisition, data preparation and subsequent event detection and classification of devices.

Data acquisition

Voltage and current measurements are used as input for NIALM. Current sensors are most suitable to recognize plugged in devices as they register all the electrical device's state changes and therefore are able to disaggregate the individual devices. Adding voltage information enables to trigger the current sensor to the zero-crossing of the voltage. These further increases the accuracy of the total power consumption measurement and phase shifting can get observed.

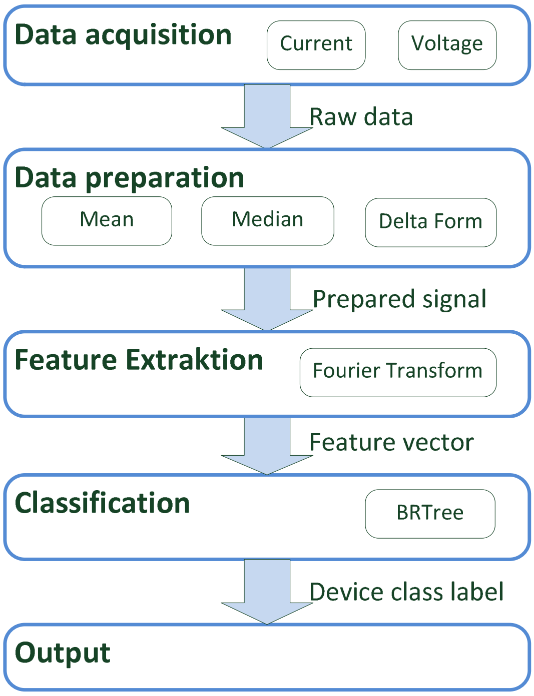

Figure 1 Processes to recognize the devices implemented in the NIALM Framework

According to [8] and [9] the sampling rate of the sensors is a very critical part of NIALM: the higher the sampling rate, the better appliances are recognized. In our application we measured voltage and current at a sampling rate of 50 kHz. For comparison, this high sampling rate was subsampled to different lower rates. Although it is possible to increase signal quantization with down sampling methods, no quantization correction was performed in our case to stay as close as possible to an industrial application. The evaluation of the sampling rate is further detailed in [5].

We use a sampling rate of 5 kHz in our application. On one hand it is a value that standard low power microcontrollers are still able to capture and process; and on the other hand it achieves high recognition accuracy. According to Armel [8] 16 to 32 devices can be accurately recognized with a sampling rate of 5 kHz. She did not provide recognition accuracy information achieved with this amount of devices. Instead of recognizing up to 32 devices with 5 kHz, [5] separated all possible devices to 9 classes to maximize the recognition performance.

Furthermore using 5 kHz allows the calculation of different features using algorithms such as Fourier Transform (FT), Wavelet Transform (WT), Root Mean Square (RMS) or offset (OF) values. Such detailed features cannot be calculated with macro level frequencies.

Data preparation

The aim of data preparation is to get stable signals. This chapter presents different methods of noise reduction to decrease the recognition complexity.

A NIALM system measures the sum of the power consumption of all simultaneously running devices (i.e. the sum curve). Assuming all N devices have only one single device state and a maximum number of k devices running simultaneously, the algorithm has to be trained with C classes. Thus it trains on all device state combinations. The combinatory equation (1) shows the dependencies.

$$C = \binom{N+k}{k} \tag{1}$$

With k = 5 and N = 11 already 4368 classes have to be trained. Since this is not computationally feasible, most NIALM researchers use delta curves to reduce the exponential complexity. A delta curve is defined as the difference between two measurements and assumes that at any point in time during two measurements only one device changes its state between these measurements. If a device changes its state, the delta curve only shows that state change and not taking the running devices into account. Thus, the NIALM algorithm only knows individual device states instead of all possible device combinations. The graph in Figure 4 shows our proposal to calculate the delta curve from the sum curve. The algorithm is detailed in the following:

1. Sampling of current and voltage over two fundamental periods of the 50 Hz AC signal (40ms). See typical results for a current waveform in Figure 2. This 50 kHz signal is down sampled in further processes to 5 kHz.
2. Compute average over both periods resulting in a single period. The curve resulting from averaging the current is shown in Figure 3.
3. Repeat step 1 and 2 every second.
4. Take 3 consecutive averaged periods and apply a median function at every point of the period. The resulting curve is called window and can be seen in Figure 4.
5. Subtract two windows with a distance of four windows in between. See an example in Figure 4.
6. Run the feature calculation and the classification algorithm on each subtracted window.

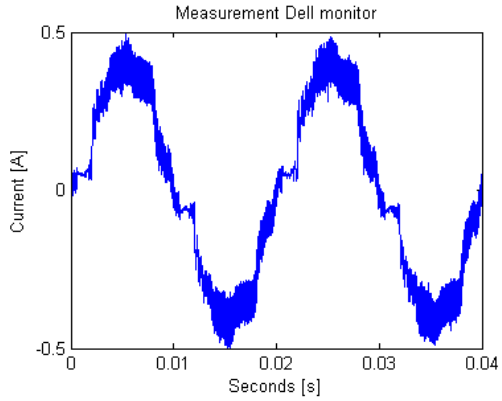

Figure 2 Raw data sample from our current sensor

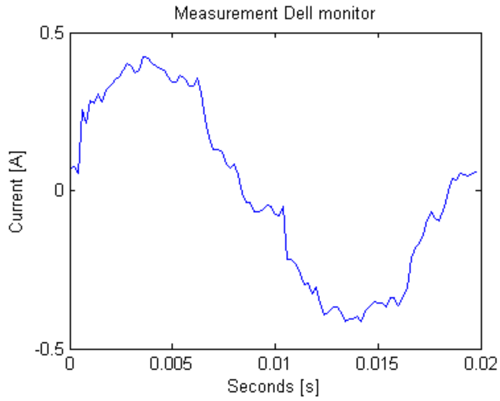

Figure 3 Down sampled signal with mean value calculation from raw data sample

In Figure 4 each small rectangle (M1 to M12) represents one mean curve as it is shown in Figure 3. These curves are sum curves thus representing all simultaneously running devices. Three of these sum curves are calculated to a window with the function $W_i = median(M_i, M_{i-1}, M_{i-2})$. The yellow triangle indicates an event where a device is switched on or off. All green windows (combination of three rectangles representing a single measurement period from step 2) show the sum curves of the running devices before the event whereas the blue windows show the new sum curve after. Red windows are undefined because they capture the intermediate current changes: When a device is switched on/off, it takes time before its power consumption settles. We use these intermediate windows to further increase recognition accuracy.

Using a distance of four windows when subtracting two windows in step 5, allows us to recognize the same device state change several times: the 4th window before the event is subtracted from the first window after the event, the third window before the event from the 2nd after the event, the 2nd before the event from the 3rd after the event, etc. Thus the event shows up on average four times (see Figure 4). Because of that the recognition accuracy is improved. The same event may affect 3 to 5 measurements depending on how long it takes the device state change to settle.

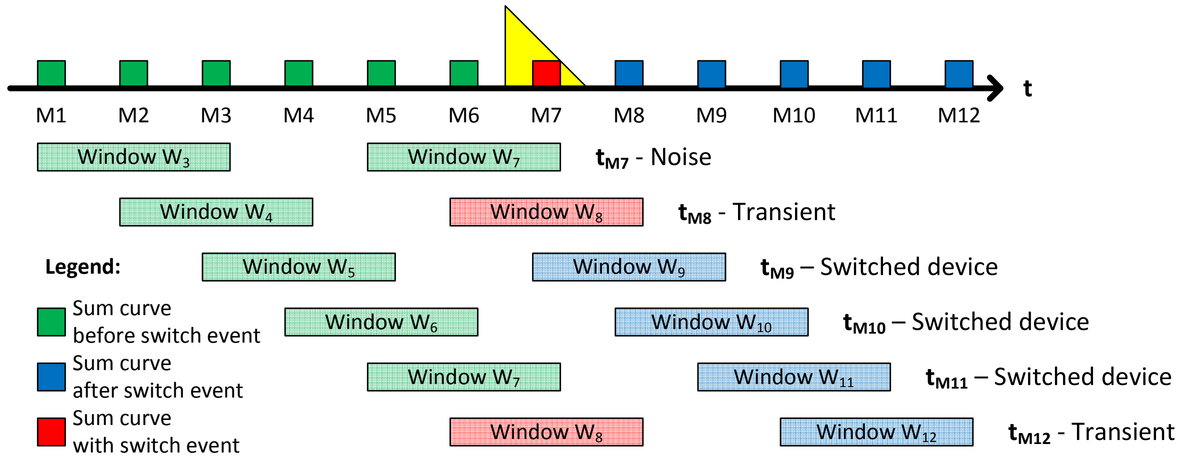

Figure 4 Event detection process to get stable events multiple times

Feature extraction

The measured micro level data makes it possible to calculate a variety of different features from the input vectors of voltage and current. Features are important for machine learning algorithms to compress the data to important property characterizing the individual devices. However, the more features that are used the higher the complexity and computation time. Additionally, with an increasing numbers of features the risk of algorithm over-fitting increases. Over-fitted classification algorithms tend to classify samples wrong if they just differ slightly from the training data. One reason for over-fitted systems is redundant information, which commonly appears in large feature vectors. The feature evaluation in our work focused on small feature vectors to increase robustness.

A feature vector evaluation shows that the parameters of the WT achieve the best recognition accuracy. We looked at the recognition performance of different classification algorithms comparing parameter distributions and using evaluation tools such as WEKA [10]. However, this feature vector is computationally expensive what makes it difficult to calculate it in real-time on a low power micro-controller. To guarantee real-time performance a FT is used instead, which performs almost as well as the WT.

Low order odd harmonics up to the 11th order are used from the FT. In addition, the complex power value was added to the input vector. In total, the feature vector contains eight parameters. Theoretically a sampling rate of 1.1 kHz would be sufficient to calculate this feature vector, but comparisons in [5] found that a higher sampling rate increases the quality of low frequency features.

Another reason for using low order harmonics in our feature vector is that many modern devices use DC converters. A common low power DC converter, as used in electronic devices, has a characteristic current consumption as given in equation (2).

$$I_{AC} = \frac{4 \cdot I_{DC}}{\pi} \cdot \sum_{k=1}^{\infty} \frac{\sin\big((2k-1)\omega t\big)}{2k-1} \tag{2}$$

Equation (2) states that the amplitude of each harmonic is inversely proportional to its order. That means it is difficult to measure high-order harmonics with a limited quantization of the signal. On the other side it also shows that the FT is a suitable tool to describe electronic devices with its harmonics.

For our purpose, the most important information of the FT signal is located in the absolute part [5]. The phase information of higher harmonics has low relation to the device itself. If the phase information is ignored, the feature calculation must be performed after the delta curve calculation so the sum curve criterion [5] remains satisfied. This criterion is important to eliminate the influence of the other sum curve devices. Our method calculates the delta curve from the voltage and current values before the feature vector is extracted. In favour of more accurate values the memory efficient variant has been renounced, which would calculate the feature vector before the delta curve.

Device identification

The extracted feature vectors from the previous steps are used to classify the devices using machine learning algorithms. Different supervised machine learning algorithm concepts which adopt their behaviour from experience were studied in [5]. The best performance is reached with the BFTree algorithm from the software workbench Weka [11]. The BFTree was used with the configuration “BFTree –S 1 –M 2 –N 5 –C 1.0 –P POSTPRUNED”. It builds a decision tree that trains with the Best-First method. Basically, a BFTree is a binary tree with logarithmic complexity in memory-use and computation.

Training data

The recognition algorithm was chosen with the constraint of being able to train the recognition algorithm with a single switched on device at a time. This has the advantage that manufacturers of NIALM can train their system in advance so that it works out-of-the-box on the customer’s side from a user perspective. This process is possible through a labelling method with a limited device topology as explained in [5]. Thus, the device topology must not contain the actual user devices for the algorithm training; it easily can be done with the manufactures device topology.

Therefore each device was measured isolated from other devices first. 32 devices and 64 different device states were measured. Only device states with a minimum stable duration of about 10 seconds were captured. This includes low energy consumption states (e.g. standby), highly variable devices (e.g. running computers) and variable loads (e.g. dimmable lamps or charging computers). In total, 3177 samples of isolated devices were measured. These samples were then used to train the recognition algorithm. In this dataset, the amount of measurements of devices with large device state variation is much higher. This results in a highly imbalanced data set. An equal weighted cost matrix is used to balance the data to ensure that the algorithm does not optimize its behaviour according to the occurrence of different device measurements. So each class is equally likely to get recognized.

In our application, the training data was captured over a short time period. Considering each device state separately, the individual measurements are just a few seconds apart from each other. Therefore, the noise in these measurements differ just little compared to measurements from other days with different environment variables. Algorithm training with small variance on the data, as used in our application, often suffers from over-fitted algorithm systems.

Test data and validation method

Test data was measured as close as possible to real applications. Compared to the training set, the sum of different devices using electrical power simultaneously was captured. As a result, the test set is independent from the training data and can be used to detect over-fitting of the algorithm. A challenge in NIALM is to obtain corresponding data for the evaluation of the algorithm, as long time intervals have to be labelled with true switching events. Without labelled data a system cannot be validated, because it is unknown whether an event was correctly detected by the NIALM system from the sum curve. Figure 5 explains our validation tool in more details. In future work our system will get validated on public data such as from [7].

A selection of devices of the training set was connected to our NIALM data acquisition system. A KNX actor switched the devices randomly on and off and logged the corresponding time of these switch events. The NIALM system measures just the sum curve and tries to detect the individual device states. The validation was done by comparing the log file from the KNX actor, which shows the true events, with the power log file recorded by the NIALM system.

The test measurements were spread over 6 days, thus incorporating noise conditions from different days and daytimes. Compared to the training set, no cost matrix has been used, because real environment data would be imbalanced as well.

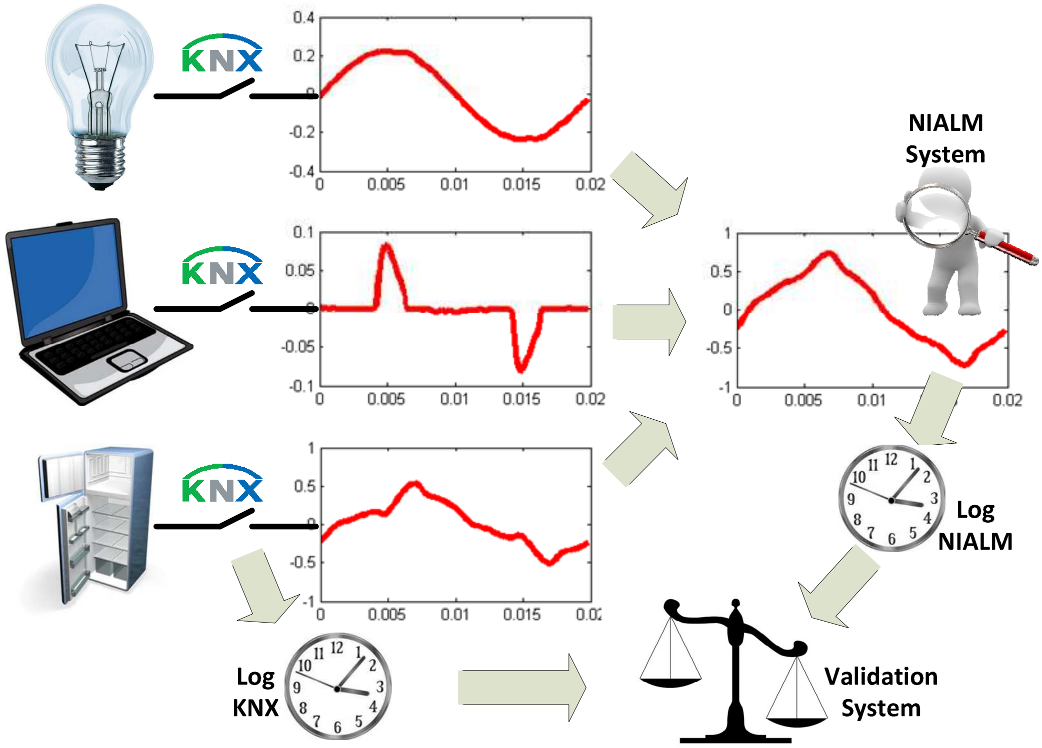

Figure 5 Validation of the NIALM System with KNX to generate a predefined behaviour of the devices

Labeling

To get accepted by users, NIALM has to achieve a minimum overall recognition accuracy of 80 to 90% [12]. This accuracy includes the event detection and the classification step. The challenge is that most households exhibit a rising number of electronic devices. One way is the user has to update the algorithm with every new device at home. Such systems suffer from decreasing performance rate over time as the total number of trained devices increases. Another way is the algorithm has to be trained to all possible devices in advance from the manufacture. Both approaches are unrealistic for the mass market. To train new electronic devices the user at home has rarely control over all device states (e.g. fridge). For the manufacturer, it would be very cost intensive initially and maintains work as there are already too many different devices on the market.

In our approach, we categorize the data for training the algorithm according to the normed current form. The norming condition was defined such that the mean current over the measurement time interval equals one. Equation (3) shows how the normed current form is calculated: $i(n)$ is the measured current vector, $i_{Normed}(n)$ is the normed current form and N is the amount of samples in a measurement.

$$i_{Normed}(n) = \frac{N}{\sum_{k=1}^{N} i(k)} \cdot i(n) \tag{3}$$

At the moment, we categorize devices into 9 classes based on a similar wave form of the normed current signal. The classes are described in more detail in [5]. Based on these classes, the NIALM algorithm is able to inform users on e.g. whether they spend most of the energy bill on lighting, electronic devices or on other device categories. This method has the advantage of a constant number of classes such that the recognition performance doesn't depend on the number of devices in a household. Thus adding a new device neither requires retraining nor affects recognition performance. Another advantage is that statistically, a lower amount of classes to recognize usually increases the recognition performance. However there is a trade-off between the amount of information available for the user and the recognition performance.

Working with delta curves allows the algorithm to identify one switching action at a time. If more than one device changes its state simultaneously, a NIALM algorithm based on delta curves can ideally only identify one of them. This typically happens with e.g. switching on power strips. With normed current curve classification the algorithm is able to classify all simultaneously switched devices as long as they belong to the same class.

Noise

The exact noise amount and form is always an unknown value. Each component of the household's power grid can be a source of noise for the NIALM measurement system. Long connections have different impedances or reflections of signals. The unforeseeable consumption part of a device is interpreted as noise: the algorithm interprets the part of a signal that differs from their training curves as noise. The most significant noise source originates from switched on appliances. Devices like a common halogen light bulb are devices with low noise injection, but there are also devices with high consumption variation. That means noise differs from measurement to measurement. Noise also changes due to environment variables.

Combining the algorithms of event detection and classification poses the problem of how to train the machine learning algorithm to noise. In real applications, it is common that environment variables change over time and thus also noise changes over time. Noise samples that represent all these changes are needed to make the algorithm resilient to noise. These samples are added on the recognition algorithm. A comparison of different types of noise signals will be revealing about it. The following types of noise are compared:

The different types of used noise are the following:

Training data: The noise is calculated from the training dataset by subtracting two measurements of a certain device state from each other. This process is repeated up to 20 times with randomly chosen device states. Finally, the differences are summed up to one total noise curve.

Test noise: The sum curve of six switched on devices was measured periodically. The difference between two randomly chosen measurements was then used as noise.

XX mA: Artificial noise is calculated. The form of noise is white Gaussian noise with a variance of 20, 40, or 80 mA.

Results

A comparison of the recognition performance with different noise signals is shown in Table 1 and Table 2. The rows list different noise datasets that include measured and artificial noise. The columns list the different training datasets. For these, the measured isolated devices were overlaid with artificial noise. Typically noise on training data reduces the recognition performance of the algorithm, and also reduces the chance of over-fitted systems. A performance increase with more noise on the training data typically is a sign for an over fitted-system. All comparisons distinguish between event and total recognition. The event detection differentiates between device and no device whereas total recognition also tries to detect the correct label.

In Table 1 each of the 3998 test measurements from the test set was evaluated separately. The order of the data does not matter. Thus each sample was treated as an event. These results are based on highly imbalanced data. For example 2754 measurements show just noise signals. So if an algorithm classifies all measurements as noise it already reaches a recognition accuracy of 69%. The result of this evaluation procedure is shown in Table 1.

Table 1 Comparison of the recognition performance of the NIALM algorithm with different noise signals. The event column shows the percentage of correctly recognized events and the total column the percentage of also correctly recognizes classes

Training / Noise	No noise Event	No noise Total	20 mA Event	20 mA Total	40 mA Event	40 mA Total	80 mA Event	80 mA Total
Training data	92.8%	81.2%	**93.2%**	**85.6%**	**94.1%**	**88.5%**	**96.5%**	**90.1%**
Test noise	90.7%	79.1%	78.5%	72.1%	81.0%	74.9%	84.5%	77.6%
20 mA	88.4%	76.2%	88.6%	80.3%	-	-	-	-
40 mA	95.7%	83.5%	-	-	**96.4%**	**90.4%**	-	-
80 mA	52.7%	39.2%	-	-	-	-	**97.8%**	**92.7%**

Users are generally not interested in how many samples with noise are classified as noise (Formula 4 cell: True negative). They are interested in how many switching events occurred and which device class changed its state. Based on the data in Table 1, the results in Table 2 show an evaluation where TN is factored out. Formula (4) describes the updated calculation of the performance rating.

$$\begin{array}{ccc} \boldsymbol{classified\ as} \rightarrow & \boldsymbol{Event} & \boldsymbol{NoEvent} \\ \boldsymbol{Event} & TP\ (True\ Positive) & FN\ (False\ Negative) \\ \boldsymbol{NoEvent} & FP\ (False\ Positive) & \cancel{TN\ (True\ Negative)} \end{array}$$

$$Performance = \frac{TP}{TP + FP + FN} \tag{4}$$

When TNs are ignored the result is more likely to reflect the interests of the user. To improve recognition accuracy a basic error correction method was applied to ignore single misclassifications. This correction is possible due to the chosen kind of delta curve calculation. Therefore four measurements are taken on average during an event (see Figure 4). If those four measurements contain the same classification result at least three times it is classified as a new event and otherwise as noise. The algorithm is shown below:

1. Determine the absolute majority of device classes amongst the last 4 windows. (A majority is reached if at least three of the measurements are recognized as the same device class)
    a. If no majority exists, classify it as noise
    b. If a majority exists classify it as that device class, if not noise
2. Look at previous event
    a. Event, if different to previous
    b. No new event

Table 2 Comparison of the recognition performance of the NIALM algorithm with TN ignored and correction algorithms applied.

Training / Noise	No noise Event	No noise Total	20 mA Event	20 mA Total	40 mA Event	40 mA Total	80 mA Event	80 mA Total
Training data	82.3%	59.3%	81.2%	69.3%	**90.8%**	**83.2%**	**90.6%**	**86.4%**
Test noise	83.3%	61.8%	65.7%	60.7%	69.1%	63.5%	73.5%	69.4%
20 mA	78.8%	56.8%	80.9%	67.1%	-	-	-	-
40 mA	87.0%	62.7%	-	-	**91.9%**	**83.4%**	-	-
80 mA	41.2%	26.8%	-	-	-	-	**93.0%**	**87.7%**

The test data contains a total of 288 true events. Recognition accuracies above 90% are coloured green in Table 1 and Table 2. 90% is a value that leads to user acceptance according to Zeifmann [12].

Discussion

Compared to most NIALM approaches we used one algorithm for event detection and classification. The advantage is that all devices are known by the single algorithm at all times. Hence the algorithm can determine if a single sample is a known device or noise.

We have developed a built-in dynamic threshold for noise classification; the majority of research into NIALM systems [13], [14], [3] uses static thresholds to recognize events. Although the sample is over an event threshold and therefore may be classified as a device class, our algorithm compares it with trained device classes. If it is not similar to one of the known classes, it still can be classified as noise.

Further if an event detection algorithm incorrectly detects an event and hands it over to the classification algorithm, the latter has to classify this incorrect event. Furthermore, the classification algorithm always delivers a result even if the to be classified sample has no close match in its database. A comparison with convenient algorithms has not been done because so far no standard approach to compare the result has been established. Traditional algorithms usually use different kinds of algorithms for the event detection and the classification to increase the performance.

Algorithm over-fitting

Table 1 and Table 2 show similar results concerning the over-fitting of the algorithm: as more noise is overlaid on the training data, the results get better. This is a sign for an over-fitted system. That means even a slight change of a measurement can lead to a misclassification by the algorithm. In other words the measured noise on the training data differs from the noise on the test data.

To reduce the incorrect classifications further, real world data should be captured over several days and at different times. However, even with training data over a long time period we still recommend to overlay artificial noise: although noise reduces the information content of the sample, it makes the algorithm more stable. In other words noise decreases the signal-to-noise ratio which makes it more difficult to get the information from the signal. Caution is required, that the algorithm does not learn specific noise types instead of the content itself.

In our results we compared different kinds of noise overlaid on the training data. The more training data we have with different noise, the better the algorithm learns the device itself. We believe that the recognition accuracy will increase again with combinations of different noise types.

Another question is the amount of noise the algorithms get trained on. A combination of different amplitudes is recommended. The variance of the highest amplitude we compared was 80 mA. That means there is 18.4 W noise power on each signal. The validation also considers an 8 W LED bulb. Therefore higher noise heavily decreases the recognition of such low power devices.

Another important result is that it still is possible to get good performance with data that lead to over-fitted systems. This is an important fact for users trying to train their system in a short time period: by overlaying their data with noise the classification performance is increased.

Training noise

Our algorithm recognizes noise. While in traditional algorithms everything below a threshold is classified as noise, our approach is more complex as noise has its distinct class just as devices.

In Table 1 and Table 2 we compare the impact of different noise signals ranging from real measured to artificial white Gaussian noise on recognition accuracy. The best result could be reached with strong artificial white Gaussian noise. Training an algorithm with a combination of several noise signals may further improve performance.

Performance evaluation

In Table 1 we classified each measurement independently. Usually, in real domestic environments switching events from devices do not occur very often. Most of the measurement variations are due to noise and not switched on/off devices. Users are mostly interested in these switching events and not in noise. Therefore it is important that correctly classified noise is not considered in the performance evaluation. Table 1 shows the performance of each sample compared to Table 2 which shows the performance of the events with some correction algorithms. With this small correction algorithm almost identical results can be achieved based on events, such as with the algorithm involving all samples individually. It is expected that the results based on events can be even higher with heuristic algorithms. Heuristics base on experience. E.g. a switched on application can't be turned on again or typically switch on duration or times could be considered.

Event detection

The confusion matrix from formula (5) shows the best classification results (Table 2). The performance of the event detection is maximized if the training data is overlaid with 80 mA white Gaussian noise. The same has been applied to noise itself. So noise has been trained with 80 mA artificial white Gaussian noise:

$$\begin{array}{ccc} classified\ as \rightarrow & Event & NoEvent \\ Event & 281 & 7 \\ NoEvent & 14 & (2696) \end{array} \tag{5}$$

In (5) all NoEvents that have been classified correctly as NoEvents are ignored as it is not interesting for the user and would distort the result. Despite that a recognition accuracy of 93% still could be reached.

Conclusion

In this paper we looked at ways to increase total recognition performance of NIALM systems. A typical NIALM approach uses a two-step algorithm for event detection and device classification. Since the first step's output is the second step's input, errors can be propagated. In our approach, a single step algorithm is used. To combine both steps a noise class is added to the existing (device) classes. Rather than first filtering noise before recognizing the actual device class as done by most NIALM approaches, our algorithm classifies each input as one of the defined classes which also includes a distinct noise class. To increase algorithm stability it was trained on data overlaid with noise. The results show that our algorithm classified devices with 87.7% accuracy and also correctly detected 93% of the events. We used a BFTree [10] and added artificial white Gaussian noise with a variance of 80 mA to all device classes when training the BFTree. We plan to explore using heuristics to potentially further increase recognition accuracy. In sum, our work considerably improves the recognition of household devices' and therefore better allows users to understand their energy consumption.

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Estimation of energy service demand and energy consumption in residential sector by 2050

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Abstract

In examining measures to mitigate global warming, it is important to evaluate future energy service demand and the devices that will be used to meet that demand in order to calculate the necessary energy consumption. Many studies have examined mitigation measures, but most of them focused on the changes in energy efficiency of devices, and examined new energy-saving devices and the cost of introducing them, providing only simple scenarios or estimations of energy service demand. Although it is important to estimate demand, the mechanism by which demand arises, including why and how much there is a demand, is complex and therefore simplifications have been made. In this study, we propose a method to quantitatively estimate the energy service demand and estimate the effects of differences in energy service demand in world 32 regions by 2050 on the difference in energy consumption.

Energy service is classified into the six types of major energy services in residential sector: heating, cooling, cooking, hot water supply, lighting, and others. The energy service demands are determined by the three factors of energy service intensity, time and size. The factors for each type of energy service were considered by the social and economic variables. For each energy service, we set the growth in each factor from the reference year up to 2050 and developed the energy service demands scenarios.

Background

To help mitigate the effects of global warming, various measures in a number of areas are required to reduce carbon dioxide emissions. In particular, in residential sectors, even the lowest quality of life requires energy usage, and the energy consumption structure in residential sectors is complicated by factors such as the local economic situation and regional characteristics. Therefore, it can be difficult to grasp a comprehensive picture of energy consumption. The World Economic Outlook (WEO) classifies the energy consumption structure in residential sectors based on income level differences [1]. Under this classification scheme, energy usage varies depending on the level of income (or development) in a region, and energy consumption services vary depending on the type of available energy.

Particularly in developing countries, such as those in Asia where the rate of development is significant, a substantial increase in energy consumption, as well as a rapid change in the energy consumption structure, is expected in accordance with population increases and economic development. Therefore, a better understanding of the demand and supply structures of energy services is of importance when considering the issues of global warming and future energy resource use.

In this study, we created scenarios concerning energy service amounts by using socioeconomic variables that influence energy consumption in residential sectors. Based on those scenarios, we then estimated energy consumption in 32 regions around the world, up until the year 2050.

The demand and supply balance for energy services

An overview of the demand and supply balance for energy services

In this study, we summarized the demand and supply balance of energy services as shown in Figure-1. The potential demand of energy services is determined by a number of social and geographic factors (climate, social environment, culture, etc.) that influence the rate of increase and decrease of energy services. However, in reality, the real demand is occasionally lower than potential demand, because of income and physical limitations (undeveloped infrastructure, and so on), depending on the level of local economic development. In this study, we defined the expression coefficient as the ratio of potential demand and real demand. Conversely, the supply of energy services is determined by devices that provide these services, and by the energy requirements of those devices. The demand and supply balance of energy services is a relationship whereby real demand is equal to supply.

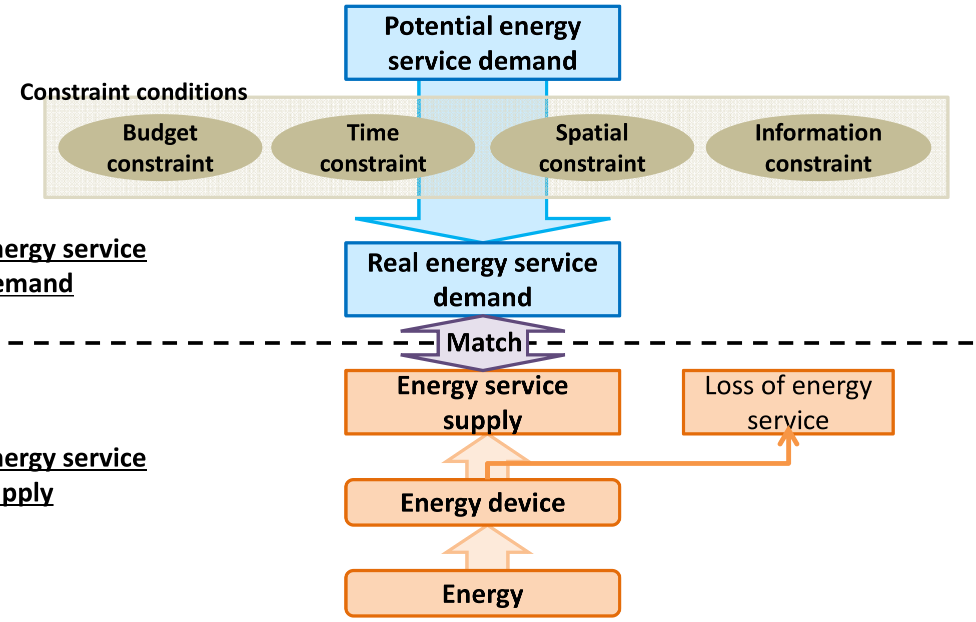


Figure-1 Demand and supply balance of energy services

Formulation

Based on the demand and supply balance of energy services as explained, we formulated the relationship between energy consumption, the real demand of energy services, and energy devices.

The energy consumption (E_r^s) of each energy (l) and service type (s) is related to the real demand of energy services (D_r^s) and energy devices, as shown by Equations (1) and (2). Thus, by multiplying the share ($cnv_r^{s,k}$) and energy intensity of each device(k), and taking their sums for each type of device, we obtain the average energy intensity of devices for each service type. From this result, and the real service demand, we obtain the energy consumption of each energy or service type.

$$E_r^l = \sum_k E_r^{k,l} = \sum_s \left(D_r^s \cdot \sum_{k\in SK(s)} cnv_r^{s,k} \cdot ef_r^{k,l} \right) \qquad (1)$$

$$ES_r^s = D_r^s \cdot \sum_l \sum_{k\in SK(s)} \left(cnv_r^{s,k} \cdot ef_r^{k,l} \right) \qquad (2)$$

In the above formulae, the share of a device is the ratio of service that a device, *k,* shares in a device group, *SK*(*s*), which provides a certain service under the conditions indicated by Equation (3):

$$\sum_{k\in SK(s)} cnv_r^{s,k} = 1 \qquad (3)$$

Additionally, the energy intensity ($ef_r^{k,l}$) is the reciprocal of the energy efficiency, and represents the energy consumption required to provide a unit of service. In this study, it is defined as in Equation (4):

$$ef_r^{k,l} = E_r^{k,l} / D_r^{k,l} \qquad (4)$$

Estimation method

In this study, based on the demand and supply balance in energy services as explained, we estimated the energy service amounts in each region until 2050. Using the estimation result and utilizing technological scenarios involving energy devices, we then estimated future energy consumption amounts. In this study, since we focused on the estimation of energy service amounts, we decided to prepare technological scenarios involving the development of energy devices, among other factors. In this estimation, we classified the world into 32 regions, and implemented eight energy types and six service types. The contents of each setting are shown in Table-1 to Table-3. The “biomass” of an energy type refers to conventional biomass. These classifications affect a reliability of analysis. In this paper, we used the following classifications and will need to consider the classifications for a better analysis.

Table-1 Region classification

Code	Name	Code	Name	Code	Name
JPN	Japan	XCS	Central Asia	XEWI	Iceland/Norway/Switzerland etc
CHN	China	XME	Other middle east	XEEI	Belarus/Croatia/Ukraine
IND	India	AUS	Australia	XENI	Other Europe
IDN	Indonesia	NZL	Newzeland	RUS	Russia
KOR	South Korea	XOC	Other oceania	MEX	Mexico
THA	Thailand	CAN	Canada	ARG	Argentina
MYS	Malaysia	USA	United States of America	BRA	Brazil
VNM	Vietnam	XE15	EU 15 in Western EU	XLM	Other Latin America
XSE	Other south-east Asia	XE10	EU 10 in Eestern EU	ZAF	South Africa
XSA	Other south Asia	XE2	Bulgaria/Romania	XAF	Other Africa
XEA	Other east Asia	TUR	Turkey		

Table-2 Energy type

Code	Name	Code	Name	Code	Name	Code	Name
BM	Biomass	OL	Oil	LPG	LPG	EL	Electricity
CL	Coal	NG	Natural gas	HT	Heat		

Table-3 Energy service type

Servide	Definition
Heating	Heating living space. Includes heating of whole buildings and rooms, and keeping the body warm by heaters etc.
Cooling	Cooling living spaces. In our research this covers only the use of air conditioners to reduce temperatures throughout rooms.
Hot water supply	Hot water supply for washing.
Cooking	Cooking food.
Lighting	Illuminating a room.
Others	Energy service not included in the above. Typical examples would refrigerators, televisions and so on.

Overview of the estimation of energy service amounts and energy consumption

The estimation of energy service amounts and energy consumption consists of 5 steps. First, we prepared information concerning energy consumption, energy service amounts, and energy devices for the reference year (2010) (STEP1). For energy service amounts, we formulated an estimation formula whereby socioeconomic factors that influence the increase and decrease of each energy service amount are considered (STEP2). Based on future estimation values for social variables that constitute the estimation formula for energy service amounts (STEP3), we then estimated future energy service amounts (STEP4). In addition, we also established future technological information (STEP5), and finally obtained an energy consumption estimate.

STEP1 Information for the reference year (2010)

For the energy consumption of various energy types in 2010, we summarized the latest energy consumption by energy type data in 2010 [2] in the 32 regions of analysis. As well, we collected as much information as possible on energy consumption in each area, energy type, and energy service types, and then calculated the energy consumption ratios for each area, energy type, and service type. Based on these consumption ratios and the energy consumption values summarized from Energy Balances [2], we calculated the energy consumption in 2010 for each area, as well as the energy service type.

In this study, we established 41 types of energy devices. Each device has two types of energy intensity in each service and energy type. We assumed that devices with small energy intensities are used in developed countries, and those with large energy intensities are used in developing countries.

For the share of energy devices in 2010, we used the share of each service type in each country when available; otherwise, we set the share of energy devices by using values in a neighboring area, with consideration of data concerning the diffusion rate of devices, and social and economic situations.

Information regarding energy intensities in Japan was obtained from the *Catalog of energy conservation devices* [3]. The relevant information concerns the energy intensities of the devices sold most recently (the directly obtained information is the energy efficiency). Therefore, these values are expected to be lower than the average energy intensity of the energy devices actually in use. In this study, considering the average life span of devices in Japan, we took the energy intensities of the devices sold in 2005 as the average of the energy intensities of the devices used in 2010. The energy intensities of Japanese devices are small, so we set the energy intensities of devices overseas in accordance with the following rules:

- For developed countries
  In developed countries, we assumed that devices with the same energy intensities as in Japan are generally used. However, it is reported that the energy intensities of these electric appliances are slightly larger than those of Japanese origin, and we therefore set the energy intensities of electric appliances to values that are about 10% larger.

- For developing countries
  In developing countries, assuming that the energy intensities of devices using fossil fuels are larger than those of Japanese origin, we set the energy intensities to values about 10% larger than those of devices used in developed countries. For electric appliances, we set the energy intensities of air conditioners to values about 30% larger, and in contrast, we set the energy intensities of devices that provide other services to values about 30% lower. For other demands, depending on the development of an area, electric appliances such as lighting devices, refrigerators, TVs, and other types, are introduced. Therefore, for devices that provide other services, only the energy intensity of lighting devices is assumed to be smaller than the average energy intensity of other electric appliances, and we set the energy intensities as mentioned above.

We calculated energy service amounts in the reference year from energy consumption information retrieved from each area, energy type, and energy service type, as well as the intensities and the share of energy devices.

STEP2 Relational expressions between social variables and energy service demand

We assumed that the potential demand of energy services was related to each social variable as shown in Equation (5) to Equation (9). In this study, we set the real demand of service per capita in each area, assuming that the real demand of service per capita in Japan is 1.

We also assumed that the heating demand was determined by heating area (ARH_r), a heating degree-day (HDD_r), and a coefficient of heat loss (Q_r).

$$\overline{D_r}^{"WM"} = ARH_r \cdot HDD_r \cdot Q_r \big/ \left(ARH_{"JPN"} \cdot HDD_{"JPN"} \cdot Q_{"JPN"} \right) \quad (5)$$

As well, cooling is determined by cooling area (ARC_r), a cooling degree-day (CDD_r), and a coefficient of heat loss (Q_r), and the potential demand is expressed as in Equation (6):

$$\overline{D_r}^{"CL"} = ARC_r \cdot CDD_r \cdot Q_r \big/ \left(ARC_{"JPN"} \cdot CDD_{"JPN"} \cdot Q_{"JPN"} \right) \qquad (6)$$

Equation (7) is a relationship between cooking demands, cooking intensity (UCK_r), and the frequency of in-home dining (REH_r):

$$D_r^{"CK"} = UCK_r \cdot REH_r / (UCK_{"JPN"} \cdot REH_{"JPN"}) \qquad (7)$$

For hot water supply demand, we assume the following (Equation (8)) for hot water supply demands on a per capita (PHW_r) basis:

$$\overline{D}_r^{"HW"} = PHW_r / PHW_{"JPN"} \qquad (8)$$

For lighting demand, we assume that it is determined by floor area (ARL_r), as shown in Equation (9):

$$\overline{D}_r^{"LT"} = ARL_r / ARL_{"JPN"} \qquad (9)$$

Other demands include various devices such as TVs, refrigerators, and other home appliances. With other demand types, it is unrealistic to distinguish between potential demand and real demand, because unexpected demand is expressed as disposable income increases. In this study, we assumed that other demand types can be explained by GDP per capita (GDP_r) (Equation (10)):

$$D_r^{"OT"} = GDP_r / GDP_{"JPN"} \qquad (10)$$

STEP3 Future estimation of social variables

Floor area

The floor area was used to estimate the service demands of cooling, heating, and lighting. We set future floor area as based on the relational expression between past data concerning floor area per capita, and the GDP per capita in each area.

We collected the latest available information on floor area per capita in each region [4], and the relationship with GDP per capita [5] in that year is shown by Equation (11). Figure-2 shows the relationship between the floor area in each region and GDP.

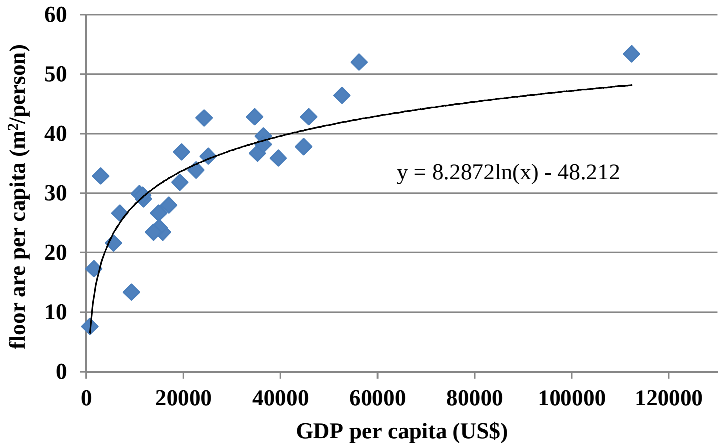


Figure-2 Relationship between the floor area in each region and GDP

Floor area per capita(m2)=8.72872*ln(GDP per capita(US$))-48.212 (11)

As shown in Figure-3, as GDP per capita increases, the floor area per capita also increases. However, there is a discrepancy between the floor area per capita values obtained by Equation (11) and actual values. We corrected this difference at the reference year, and then set the projected floor area by using a future scenario of GDP per capita.

Rate of in-home dining

We used the rate of in-home dining to estimate cooking services. The relationship between the rate of in-home dining (as based on money amounts) in each area in 2010, which is set from the Global Market Information Database (GMID) data [6] concerning consumption expenses for food purchases, and GDP per capita is shown in Equation (12) (Figure-3).

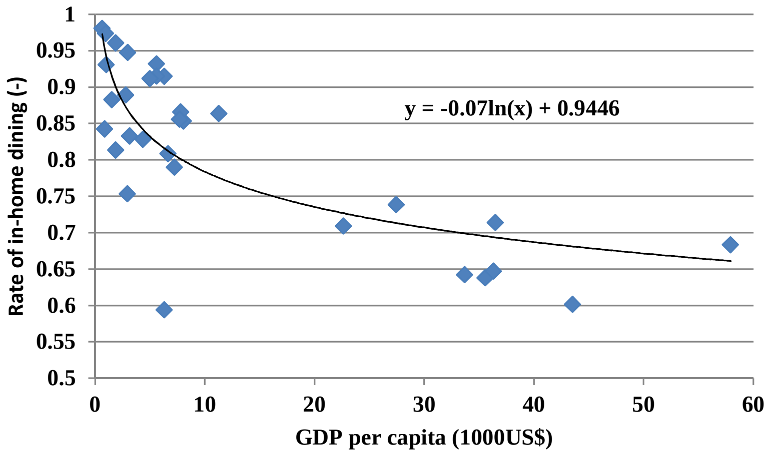


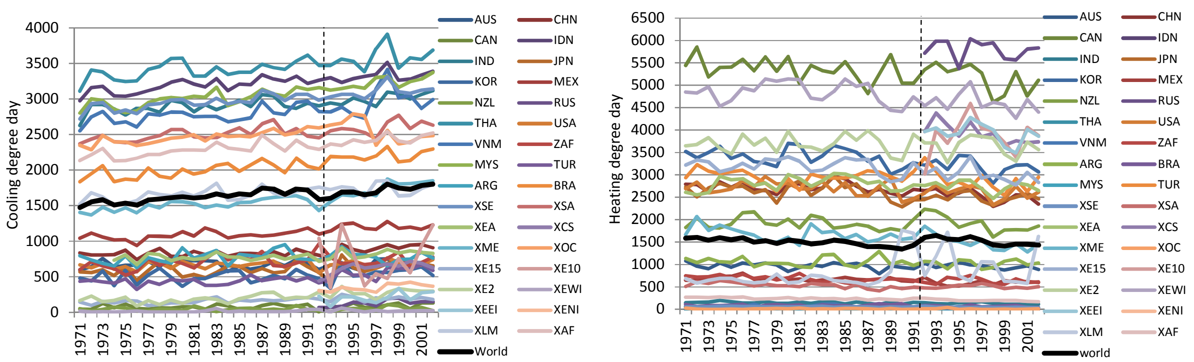
Figure-3 Relationship between the rate of in-home dining (as based on money amounts) and GDP per capita

Rate of in-home dining(-) = -0.07*ln(GDP per capita(1000US$))+0.9446 (12)

We found that the rate of in-home dining decreased as GDP per capita increased. However, there was a discrepancy between the rate of in-home dining obtained by Equation (12) and actual rates. Therefore, we corrected this difference at the reference year, and we set future rates of in-home dining by using future estimations of GDP per capita.

Setting of cooling and heating degree-days

Cooling and heating degree-days influence cooling and heating service demands. In accordance with Michell and Johnes [7], we set weights for the cooling and heating degree-days in each area from 1971 to 2002, based on population. Figure-4 shows the summarized results in each area. From Figure-4, we can see that there is a tendency for cooling degree-days to increase with each year, and heating degree-days to decrease with each year. These changes could be due to multiple causes, such as (1) the influence of temperature increases caused by global warming, and (2) the influence of a change in residence area distribution caused by factors such as urbanization. However, it is difficult to describe changes in cooling and heating degree-days with an equation that sufficiently incorporates those factors. Therefore, in this study, we simply used a linear approximation to discuss changes in cooling and heating degree-days in each area with each year, and we set cooling and heating degree-days until the year 2050.



(Note) Before 1991, regions which related with former Soviet nation and former Yugoslavia are not included in “world”.

Figure-4 Degree-days from 1971 to 2002 (Left: Cooling Right: Heating)

Other variables

Among the variables that determine the services indicated in Equation (5) to (10), we assumed that cooking intensity, hot water supply demand per capita, and a coefficient of heat loss, which are not explained in previous section, were unchanged from the values in 2010, because we could not obtain sufficient past information to perform future estimations.

Expression coefficient: Setting of the diffusion rate of air conditioners

For energy service demands, as previously explained, not all of the potential demand is satisfied due to factors such as insufficient infrastructure improvements. An expression coefficient is a coefficient that expresses the relationship between potential demand and real demand, and it can be difficult to concretely interpret an expression coefficient. For this reason, we tentatively considered the diffusion rate of air conditioners to be an important factor that is related to the expression of cooling services. It is apparent that the diffusion speed and the attained level of diffusion differ from area to area. Therefore, to consider the future air conditioner diffusion rate, we assumed the attained diffusion level and speed to be as follows: first, for the attained level of diffusion, we assumed that:

- an area where the cooling degree-days are more than or equal to 1500 attains a diffusion of up to 95%.
- an area where the cooling degree-days are more than, or equal to 600, and less than, or equal to 1500, attains a diffusion of up to 75-80%.
- an area where the cooling degree-days are less than, or equal to 600, attains a diffusion of up to 40%.

For the diffusion speed, we assumed that there is no diffusion in an area where the attained level is already considered to be at a maximum. On the other hand, for an area where diffusion is in progress, we set a neighboring area that has a similar diffusion curve, and we assumed that diffusion proceeds in accordance with the same diffusion curve in that area.

STEP4 Estimation of future energy service amounts

Based on the results of STEP2 and STEP3, we estimated energy service amounts per capita, and those of the entire area until 2050. We used SSPs(Shared Socio-economic Pathways) [8] for the GDP and population scenarios that are required for future estimations. SSPs have 5 scenarios and each SSP1-5 are “low challenges for mitigation and adaptation”, “moderate challenges for mitigation and adaptation”, “high challenges for mitigation and adaptation”, “high challenge for mitigation and low challenge for adaptation”, and “low challenge for mitigation and high challenge for adaptation” respectively.

STEP5 Setting future technological scenarios

We set the information concerning future energy devices based on two fundamental ideas. First, we assumed that (1) the energy intensities of all energy devices will become smaller. Additionally, we assumed that (2) electrification basically proceeds, or in other words, the shares of electric devices will increase. First, we set the share of electrical devices in each energy service type in 2050, and we assumed that they would change linearly toward 2050. The following are scenarios involving the energy intensities of energy devices:

- Energy devices in developed countries
  For electric cooking devices and electric hot water heaters, we assumed that the energy intensities in 2050 will be 1.053. For air conditioner for cooling and heating, we assumed that energy intensities will be 0.111 and 0.097 respectively. For other heating, cooking and hot water supply devices which use fossil fuel, we assumed that the energy intensities in 2050 will be smaller value compared with that in 2010. We also assumed that the energy intensities of other devices will remain unchanged from those observed in 2010.

- Energy devices in developing countries
  First, in China, we assumed that the energy intensities of devices in 2050 will equal those in developed counties. In areas where the GDP per capita will be more or equal to China, we assumed that the energy intensities of devices will equal those in China. And, in areas where the GDP per capita in 2050 will be less than or equal to China, we set energy intensities by using a future scenario of GDP per capita, based on the relationship between the GDP per capita in China and energy intensities (hereafter referred to as an energy intensity curve).

Estimate of energy consumption

Based on the energy service amounts in STEP4 and the technical scenarios of future energy devices set in STEP5, we estimated the energy consumption of each area and each energy type until 2050.

Results

Future estimations of service demand

Figure-5 shows the estimated future energy service demands. There was a significant difference in GDP per capita depending on the SSP scenario and as a result, energy service demands significantly differed from scenario to scenario.

For heating, cooling, lighting, and other services, SSP5 showed the largest growth in energy service amounts. On the other hand, SSP5 showed the smallest growth in the energy service amount for cooking. In Japan, the energy service amount for heating in 2050 is 95% as compared with those in 2010. In China, it is also 1.19 times larger. In Asia, as infrastructure improves, a demand will be expressed significantly. We observed that various energy services will be expressed in the 40 years until 2050 due to significant economic growth, but in Africa, the expression of energy services is less significant than that observed in Asia, because of much slower economic growth.

In contrast, in SSP3, since economic growth is not significant, the growth rates in the energy service amounts for heating, cooling, lighting, and other services are not substantial. Even in such a case, we observed that the heating service in XSA in 2050 will be 3.21 times larger as compared with 2010 values. Heating service demand of some countries which temperature is high will be 0 because of heating degree days assumption.

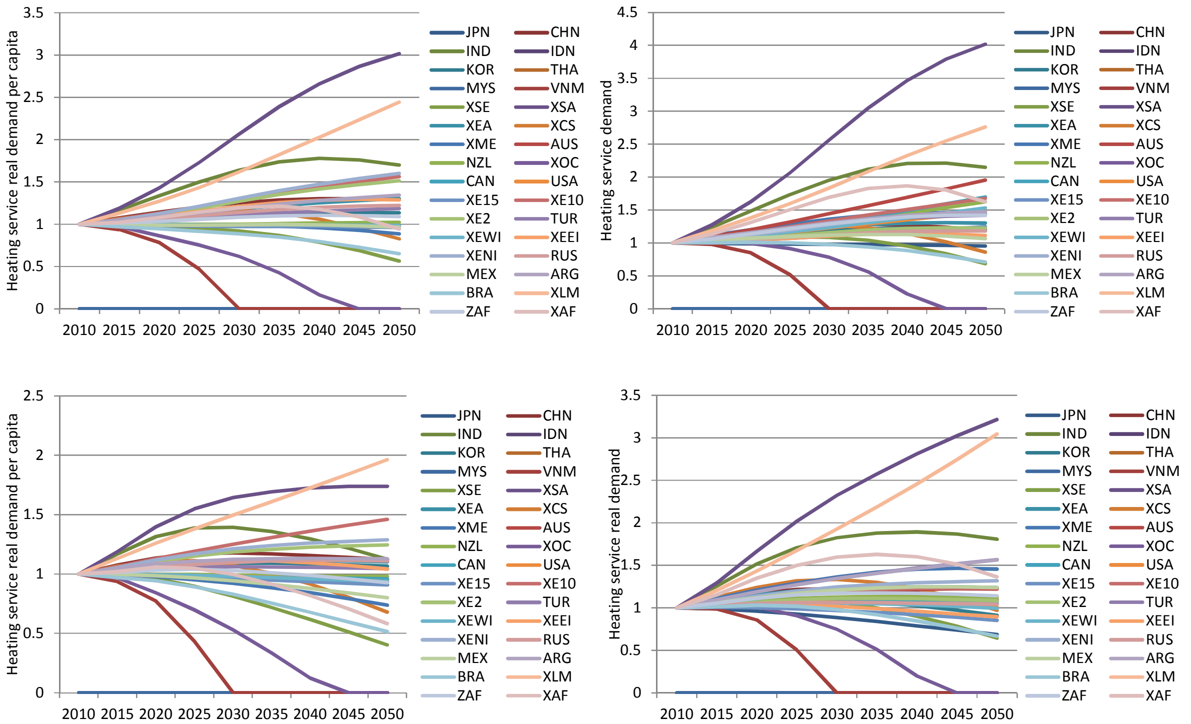


Figure-5 Heating service real demand (Upper: SSP5 Lower: SSP3)

Future estimations of energy consumption

Figure-6 and Table-4 show the result of future energy consumption estimates for some Asian countries. For energy devices, since we set scenarios of electrification progress and improvement of energy efficiency, energy consumption rates do not increase at the same rate as the growth in service demands. The most significant growth in energy consumption was seen in SSP5, and the electricity consumption rates in 2050 will be 1.30 times larger in Japan, and 1.62 times larger in China, than those observed in 2010. In particular, in developing countries such as those in Asia, a shift in energy sources from biomass to fossil fuels such as coal and petroleum, and to electricity, is currently in progress. For example, in China, the consumption of fossil fuels will become 0.58 times larger.

Comparing various scenarios, we observed that the energy consumption in the SSP3 case displayed the lowest rate of growth. In this case, the electricity consumption in 2050 will be 0.946 times larger in Japan and 1.35 times larger in China, as compared to those in 2010.

The results from each region indicated that the growth in energy consumption is quite significant in Asia. In India, and Malaysia, the electricity consumption in 2050 will be 11.9 and 2.7 times larger than that observed in 2010, in the case of SSP5.

It is expected that electricity consumption will increase from about 1.351 times larger (China in SSP3) to 13.2 times larger (India in SSP3) in Asian developing countries, and it is expected that energy consumption increases will have important implications in the context of climate change. However, with consideration of countermeasures being implemented in each country, these differences are not negligible. At present, we set very simple relational expressions between rates of economic growth and various socioeconomic variables in order to create an estimate. However, the following points are important considerations in the accurate estimation of service demands: (1) to make future scenarios of socioeconomic variables that are not considered at present (2) setting future scenarios of socioeconomic variables, to consider a relationship between those variables and others apart from the rate of economic growth, and (3) to further examine a mechanism of how demand is expressed.

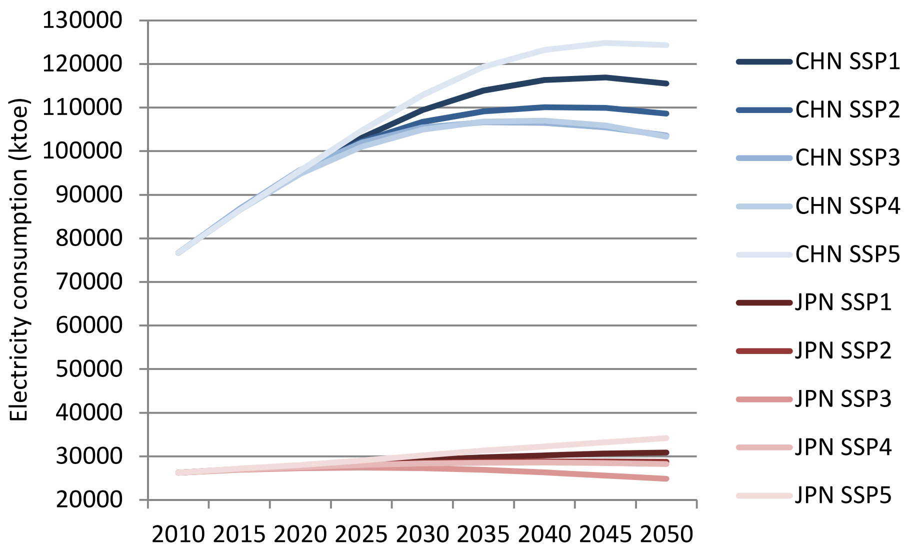


Figure-6 Electricity consumption in JPN and CHN

Table-4 Energy consumption in SSP3 and SSP5 (Unit= ktoe)

		2010		2030	2050		2030	2050
CHN	BM	201362	SSP5	139542	57337	SSP3	140563	58146
CHN	OTH	95644	SSP5	77378	55564	SSP3	79527	59296
CHN	ELY	76688	SSP5	112875	124319	SSP3	105484	103627
CHN	HET	28081	SSP5	27704	20554	SSP3	27344	20112
IDN	BM	44694	SSP5	27254	13734	SSP3	29345	16623
IDN	OTH	5998	SSP5	10807	13744	SSP3	11523	16420
IDN	ELY	5169	SSP5	18331	41527	SSP3	19481	43607
IDN	HET	0	SSP5	0	0	SSP3	0	0
IND	BM	133256	SSP5	109944	65469	SSP3	121170	84539
IND	OTH	32749	SSP5	61719	73744	SSP3	65640	91325
IND	ELY	16135	SSP5	83961	193388	SSP3	74865	212789
IND	HET	248	SSP5	242	202	SSP3	267	257
JPN	BM	23	SSP5	24	24	SSP3	21	18
JPN	OTH	21158	SSP5	14521	8320	SSP3	13291	6348
JPN	ELY	26253	SSP5	30203	34171	SSP3	27299	24836
JPN	HET	425	SSP5	527	617	SSP3	484	476
KOR	BM	34	SSP5	19	0	SSP3	17	0
KOR	OTH	12722	SSP5	12350	10498	SSP3	11373	8073
KOR	ELY	5271	SSP5	10546	15918	SSP3	9152	10313
KOR	HET	1779	SSP5	1671	1243	SSP3	1525	937
MYS	BM	1699	SSP5	1302	811	SSP3	1415	1008
MYS	OTH	679	SSP5	743	809	SSP3	806	1008
MYS	ELY	1937	SSP5	3344	5263	SSP3	2946	4186
MYS	HET	0	SSP5	0	0	SSP3	0	0
THA	BM	6752	SSP5	4666	2634	SSP3	4834	2939
THA	OTH	1607	SSP5	1744	1699	SSP3	1803	1886
THA	ELY	2894	SSP5	6010	10420	SSP3	5229	8024
THA	HET	0	SSP5	0	0	SSP3	0	0

Conclusion

In this study, we estimated future service demands in residential sectors by using socioeconomic variables, and based on those considerations, we estimated future rates of energy consumption. From the estimation results, the following three points have been revealed:

- For heating, cooling, lighting, and other services, SSP5 showed the largest growth in energy service amounts.
- In SSP3, since economic growth is not significant, the growth rates in the energy service amounts for heating, cooling, lighting, and other services are not substantial.
- It is expected that electricity consumption will increase from about 1.351 times larger (China in SSP3) to 13.2 times larger (India in SSP3) in Asian developing countries.

In addition, for future reference, it may be desirable to improve the estimation of the following three points to properly capture socioeconomic phenomena:

- to make future scenarios of socioeconomic variables that are not considered at present
- to further examine a mechanism of how demand is expressed
- to assume technology scenario carefully considering current situation

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Using a Cascading Classifier to improve the Recognition Performance of NIALM

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Abstract

People are willing to save energy yet most have little to no understanding about the energy consumption of their household devices. Non-intrusive appliance load monitoring (NIALM) is an approach to automatically measure a household's energy consumption and identify switched-on appliances. This paper presents our ongoing research on improving electric load recognition thus helping people to better understand their energy consumption.

Depending on what current NIALM approaches identify, they have either high recognition accuracy or can recognize a lot of different devices. This approach uses a two stage cascading algorithm which recognizes groups of similar devices states in the first and individual devices states in the second stage. From a user perspective, the first classifier is an out-of-the-box algorithm with high recognition accuracy due to a low number of classes. The second classifier is trained by users with specific devices they want detailed information about. Our novel approach has an overall recognition accuracy of 87% and more.

Keywords—NIALM; NILM; load disaggregation; cascade classifier; device categorization; device labelling; load recognition; machine learning algorithm; BrTree; class weighting;

Introduction

While low power consumption of electrical devices is of growing importance for users and manufactures resulting in more power efficient devices, the overall consumption is growing. In Switzerland, one reason for the increasing consumption is the growing population. Another reason is the raising number of electrical household appliances. The Swiss government published different strategies describing how the total energy consumption can be decreased in homes [1], e.g.:

a) Substitution of devices with more efficient replacements
b) Automatic switch off of unused devices
c) Visualization of energy consumption to give users a better understanding of their energy consumption

It is getting more and more difficult to identify household devices that significantly contribute to the energy consumption. New devices have many device states (e.g. a blender can have different spin levels influencing its energy consumption) and it is not straight forward to know the associated energy consumption. In addition, most users have little to no understanding about their energy consumption although they are willing to save energy.

Non-intrusive appliance load monitoring (NIALM) is one approach to face these challenges: Based on low cost measurement systems or smart meter values, NIALM automatically detects and classifies switched-on appliances. Thus, NIALM automatically assess how much energy each appliance consumes and opens new possibilities to save energy by better informing the user: Inefficient devices can be easily identified, even automatically switched off, and real time information on consumption can be provided to users to increase their energy awareness at home.

One of the major problems of NIALM is adequate recognition accuracy. According to Zeifmann [2], accuracy above 80% is required to gain user acceptance. Mathis et al. [3] showed that constant recognition accuracy has to be achieved in spite of the raising number of electrical appliances. They introduce a labelling method device groups get recognized with high accuracy. Thus, NIALM applications necessitate a trade-off between the recognition of a large number of devices versus good recognition accuracy. As fewer classes have to be recognized as more accurate a classifier gets. For example, if there are only two devices and the algorithm always recognizing the same device, results in accuracy of 50%.

To reduce the number of devices Mathis et al. introduced a different labelling method with a low number of device categories [3]. They achieved constantly good recognition accuracy. The algorithms of this method can be easily trained by the manufacturer. The disadvantage is that information about individual devices cannot be determined by their system. In this paper, we show an extension to that method which also delivers detailed information about specific devices. We propose a two-stage cascaded classifier that recognizes the device category first and the specific device second.

Related Work

A NIALM system was first proposed by Hart [4] more than 20 years ago. A good overview on NIALM research since then was compiled by Liang [5], [6]. He explains the main challenge in NIALM to reliably detect different working states of electrical devices in order to maximize the device recognition accuracy. Usually, researchers dealing with measurements based on macro level group devices and label these groups (e.g. [7], [8]), whereas researchers that use micro level data label each device. Micro level denotes sampling rates higher than the fundamental waveform of the AC signal whereas macro level denotes lower rates. To our knowledge, there is no prior work combining device group and device labelling approaches. The two stage cascade classifier described in this paper relies on both: the first stage involves the device group and the second the device state labelling approach.

This work builds on Mathis et al.'s work [3] on labelling device states to categories to maximize recognition accuracy. Further Mathis et al.'s [9] algorithm has been used in the first stage.

Methods

The first stage of the cascade algorithm detects events and classifies their device class. This stage is intended to be trained by a NIALM manufacturer and to work out-of-the-box from a user perspective. The goal of this stage is to reliably detect events and to provide a few basic functionalities: It will be able to inform users whether they spend most money of the energy bill on lighting, electronic devices or on other device categories. Additionally, information about the total energy consumption and the amount of energy used for devices that are switched on 24h a day is provided. The algorithm classifies all samples according to their normed current waveform (NL Label), see [3] for details. For the recognition and event detection the BFTree algorithm from the software workbench Weka [10] is used in [9]. This algorithm periodically classifies the feature vector $\overrightarrow{F_P}$. For every event this input feature vector $\overrightarrow{F_P}$ is sent to the second stage as an event based feature vector $\overrightarrow{F_E}$.

The second stage disaggregates individual device states that are trained by NIALM users. From the user's perspective the most interesting devices should be visualized with the best possible accuracy and as much information as possible within this stage. Improved recognition accuracy is expected as the algorithm must only analyse a selection of devices instead of all devices or device states. This approach also heavily decreases the complexity of the algorithm. The algorithm of the second stage labels the device measurements according to their device state (DSL Label).

An overview of the two stage cascading algorithm is given in Figure 1.

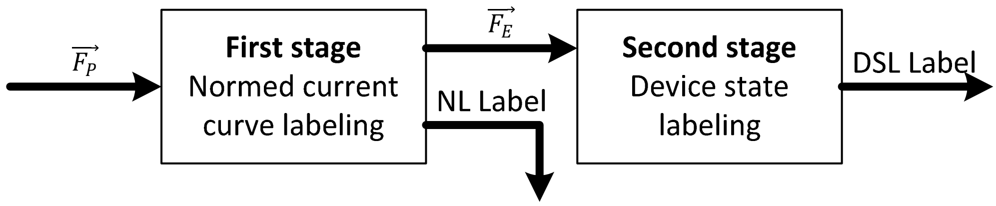

Figure 1 Schema of the two stage cascading NIALM algorithm. The first stage detects events which are then further analysed by the second stage to obtain device specific information.

Periodically feature vector $\overrightarrow{F_P}$

The quality of the input data for the cascade algorithm is of critical significance. First the voltage and current are measured at 5 kHz sampling rate. To keep the complexity of the algorithms low the delta curve is then calculated. The delta curve is defined as the difference between two measurements under the assumption that only one device changes its state between the measurements. The exact procedure is explained in [9].

From the delta curve, a feature vector is calculated. These vectors are used to decrease the amount of data and to extract features with high information content for the recognition task. Different input feature vectors have been compared in [3]. The best results of our algorithm in the first stage are achieved with a feature vector containing absolute Fourier Transform values. For this all odd harmonics up to the 11^{th} order and the complex power values were used as input feature vector. The input feature vector $\overrightarrow{F_P}$ therefore consists of eight elements and is every second calculated.

First stage classifier

In the first stage of the algorithm, a BFTree [10] classifies the input vector $\overrightarrow{F_P}$ every second on a dedicated system. That means users can have a single NIALM system at meter level or they can have more of them on specific parts of the household to improve the recognition accuracy. Each device belongs to a device category (NL Label) [3]. If the user buys a new device, there is no retraining necessary as all available devices belong to such a category. The algorithm can be trained by the manufacturer and works from a user perspective out-of-the-box. The used algorithm of this first stage was developed in [9]. There events are measurements not classified as noise. Such events are forwarded to our second stage. The new feature vector $\overrightarrow{F_E}$ is identical to $\overrightarrow{F_P}$ but occurs only on events instead of every second. A reason for the event based approach of $\overrightarrow{F_E}$ is the usually low communication bandwidth between the measurement unit and the central unit. A central unit is seen as a device that calculates trends, histories and other consumption details for visualization purposes. It can be located in the household or could be implemented as a web service. The dedicated system runs on a low power system.

A BFTree is used for the first stage classification and requires little computation thus little energy to run. A BFTree is a binary tree with logarithmic complexity in memory-use and computation. Low energy consumption of the NIALM system itself is important, because NIALM is a way to cut down the total energy consumption of a household.

The following setup taken from [9] is used to achieve optimal results: Noise is trained with white Gaussian noise with 80 mA variance and the measurements of the training devices are overlaid with the same kind of noise. This large amount of noise is necessary to avoid algorithm over-fitting.

Second stage classifier

If the first stage detects an event, the periodic feature vector $\overrightarrow{F_P}$ is forwarded as an event based vector $\overrightarrow{F_E}$ to the 2nd stage. The NL label (i.e. the recognized device class) from the first stage is unknown to avoid error propagation. The goal of the 2nd stage is to provide more energy consumption details of preselected devices. If the user is for example interested in the energy consumption of his new computer monitor he can train that device. From then he will get a detailed energy consumption history of this device without buying a separate measurement system. An example of the algorithms work is provided in Figure 2: The algorithm has exclusively trained to recognize a monitor. Thus, in this example other devices' energy consumption is of no interest to the user. The algorithm has to classify each event either as state change of the monitor or as unknown. Noise also belongs to the class unknown devices.

The biggest challenge is to differentiate between known and unknown devices. Figure 2 shows an example of two different devices. While the devices serve different purposes they have both similar power values and also a similar phase shift. If only the monitor class is known to the algorithm, the light bulb is probably misclassified as a monitor rather than an unknown device. Misclassifications mean that the user receives incorrect information and thus to false conclusions on how to save energy. Eventually users will lose confidence in the system. The more devices with similar energy signatures the algorithm has to differentiate, the lower its accuracy will be as the misclassifications amongst these similar devices will increase.

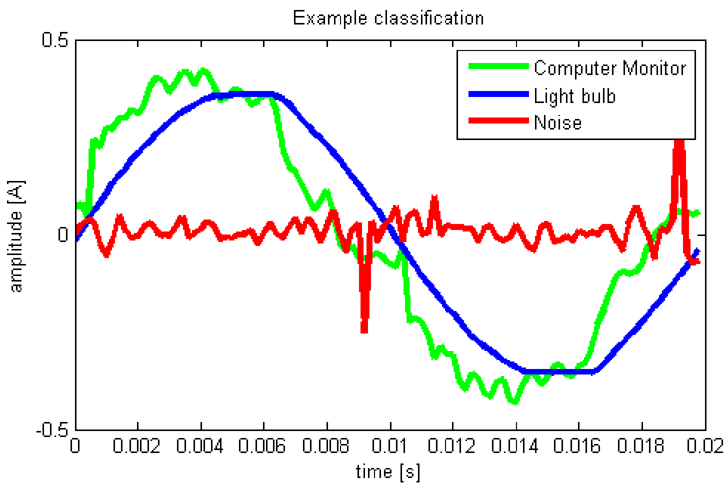

Figure 2 Sample curves of the second stage (computer monitor and noise have been trained to the algorithm, but not the light bulb)

Similar to the first stage a machine learning approach is used for device recognition in the second stage. In the following two approaches it will be presented.

Approach 1: Artificial Noise Teaching

The class unknown devices is trained with artificial white Gaussian noise in several strengths. The aim of this noise signals is to train with samples that are in combination as much as possible equally distributed over all parameters in the input vector. As the feature vector contains frequency values, white Gaussian noise seems to be a good approach with its constant spectral density. So each sample has a probability higher than zero to belong to the class unknown. Additionally a device is only classified as such if a predefined confidence probability is exceeded. In the example of Figure 2 the monitor will only be recognized as monitor if the algorithm is e.g. 95% sure it really is the monitor. Hence a Bayes approach appears quite reasonable because it is based on probability density functions. Bayes networks build a probability model of each class with interferences to each other. They already perform well in the first stage. Thus, for each sample, the probability is anyway calculated for all existing classes.

Approach 2: Device set teaching

Use the entire training data set from the first stage including noise and label all data as unknown devices. Additionally measurements of the devices the user is interested in were added to the training set. In our application they were a selection of device states from the same measurements set as already used for the training of the class unknown devices. The resulting dataset is highly imbalanced: We have a large amount of data in the 'unknown device' class and only little to train the devices the user is interested in. Each sample uses a specific weight to balance the weight of each class. Exactly the same measurements were used to teach the devices of interest to the user, as they have been already used to teach unknown devices but with different weights. Thus the algorithm deals with contradictory information. Even the artificial noise overlaid on each measurement has been used in both classes without any change.

Class weighting

The weighting of the training data is of critical importance. In the training, each sample is weighted according to their class relevance. See formula (1) for the calculation. w_c is the weight factor of the individual sample belonging to the class c, p_c is the target weight of the class c, n_c is the number of samples in that class and n the total amount of samples in the training set.

$$w_c = \frac{p_c \cdot n}{n_c} \; for \sum_c p_c = 1 \; and \sum_c n_c = n \tag{1}$$

Weighting can only be applied to classifiers that can consider such information in their training. Different weightings have been compared in this paper. The results will show a worst case scenario for the algorithm as contradictory information has been used.

Accuracy evaluation

The second stage uses the data classified as events ($\overrightarrow{F_E}$) from the first stage. True as well as falsely classified events will therefore get processed. In formula (2) recognized events from the first stage are marked blue whereas the missed events are shown in red.

$$\begin{array}{ccc} \boldsymbol{classified\ as \rightarrow} & \boldsymbol{Event} & \boldsymbol{NoEvent} \\ \boldsymbol{Event} & TP\ (True\ Positive) & FN\ (False\ Negative) \\ \boldsymbol{NoEvent} & FP\ (False\ Positive) & TN\ (True\ Negative) \end{array} \tag{2}$$

The second stage however does not get the NL label from the first stage. So even on the first stage incorrectly classified events (FP) can be classified correctly in the 2nd stage.

Dataset

The training dataset contains 64 different device states accumulated from 32 different devices. In total the dataset contains 3177 measurements of which 1000 measurements were artificial white Gaussian noise with a variance of 80 mA. The measurements of the interested device states have been included in the training set. The amount of learning curves was on average 35 measurements. After the training process the algorithm has been tested with an independent test set of 3998 measurements containing events of the following device states. These test devises have been switched on and off simultaneously and randomly as they would in real environment (see [9] for more details).

1. Toshiba Satellite Pro C850-1dx (Laptop state charging)
2. Acer LCD Monitor T231H (Monitor state on)
3. Fust Primotecq 01/07 (Ventilator state S2)
4. Osram duluxstar 23W (Energy saver bulb state on)
5. Megaman LED Classic 8W (LED light state on)
6. Osram CLAS A CL 40W (Light bulb state on)

Results

A BFTree algorithm was trained according to the second approach with the same dataset as used in the first stage. All samples were labelled as unknown devices. This set has been extended with known devices. This approach is used in all further comparisons. The BFTree from [10] was used with the configuration “BFTree –S 1 –M 2 –N 5 –C 1.0 –P POSTPRUNED”.

Algorithms

The recognition accuracy results are provided in Table 1 and Table 2. The columns show the chosen devices that our algorithms trained with. Comparisons with different weightings of each sample are listed in the rows. The weight of each sample is calculated according to Equation (1). In the following results, p_n is the weight of the unknown device class. It has to be mentioned that the results depend on the first stage. Thus all the missed events are not validated. The event detection reached an accuracy of 93%. See [9] for more detailed accuracy analysis.

Table 1 shows the result of the Bayes algorithm compared with different weighting functions.

Table 1 Device identification result with Bayes Net algorithm

Nr. Devices / Device weight	1	1+2	1+2+3	1+2+3+4	1+2+3+4+5	1+2+3+4+5+6
Each class equal weighted	**98.9%**	87.7%	70.9%	56.0%	41.4%	22.8%
$p_n = 30\%$	97.4%	**88.4%**	**78.4%**	**75.7%**	**60.4%**	**43.3%**
$p_n = 40\%$	98.1%	88.1%	72.4%	65.7%	55.2%	39.2%
$p_n = 50\%$	98.8%	88.1%	71.3%	61.9%	51.9%	34.0%
$p_n = 60\%$	**98.9%**	87.7%	72.0%	58.6%	45.5%	29.5%
$p_n = 70\%$	**98.9%**	87.7%	72.4%	58.6%	45.1%	26.1%
$p_n = 80\%$	98.5%	88.1%	72.4%	56.7%	43.7%	25.0%
$p_n = 90\%$	98.5%	87.7%	71.6%	54.1%	40.3%	22.0%

Table 2 shows the result of the BFTree algorithm also compared with different weighting functions.

Table 2 Device identification result with BFTree algorithm

Nr. Devices / Device weight	1	1+2	1+2+3	1+2+3+4	1+2+3+4+5	1+2+3+4+5+6
Each class equal weighted	87.3%	92.9%	88.4%	87.3%	86.9%	85.8%
$p_n = 30\%$	86.2%	90.7%	88.1%	86.2%	88.8%	85.8%
$p_n = 40\%$	86.6%	89.6%	88.4%	87.7%	86.2%	83.6%
$p_n = 50\%$	87.3%	90.7%	89.2%	87.7%	86.9%	**92.5%**
$p_n = 60\%$	87.7%	93.6%	89.2%	**94.4%**	**87.7%**	86.9%
$p_n = 70\%$	88.8%	**93.7%**	**92.2%**	86.7%	82.8%	86.9%
$p_n = 80\%$	93.7%	93.3%	88.4%	90.3%	67.9%	68.7%
$p_n = 90\%$	**96.3%**	89.6%	73.1%	73.5%	61.1%	53.3%

Class weighting

In Table 1 and Table 2 the best results for each combination of devices has been marked green. Results from the BFTree algorithm clearly suggest a relation between the weight of unknown and known devices. Equation (3) calculates the weight p_n of the class with unknown devices under the assumption that the dependency between known and unknown classes is linear. The rest is equally distributed to the number of devices. The factor f in Equation (3) is the rise of the function and must be verified. a_d is the number of trained devices.

Table 3 shows the results for $f = 7 \; and \; f = 8$.

$$p_n = \frac{f}{a_d + f} \; for \; f \geq 0 \tag{3}$$

Table 3 Device identification result with BFTree and dynamic weighting

Device weight \ Nr. Devices	1	1+2	1+2+3	1+2+3+4	1+2+3+4+5	1+2+3+4+5+6
$p_n\|_{f=7}$	90.3%	93.3%	92.2%	90.3%	87.3%	92.5%
$p_n\|_{f=8}$	96.2%	93.3%	88.4%	90.3%	87.3%	87.3%

Discussion

Algorithm

Additional to recognizing trained devices, a classifier must incorporate the possibility that an event does not belong to any of the known devices. We looked at two strategies to achieve that: first, using a probabilistic and only accept the recognition result if its associated confidence value is above a predefined threshold. The second approach is to introduce a separate "unknown" device class. Both approaches were tried and the second approach was found to perform better.

When trying the probabilistic approach, we found that in our test set, the class probability value of Bayes networks had no relevance to true classification. In other words, there were as many test samples with a high confidence classified incorrectly as there were incorrectly classified samples with low confidence. Using different threshold values for the minimum confidence value did not improve the result. Because of the lower accuracy compared to the second approach, we decided to only continue with the said "device set teaching" strategy.

Using a BFTree algorithm in the second approach performed better compared to the Bayes Network in the first approach. The decision tree finds the most significant parameters with the Best First algorithm. The tree also weights each training instance properly even if there is contradictory information in the training set. We tested different configurations ranging from one to six device classes and reached at least a recognition accuracy of 87%.

Class weighting

The results strongly depend on the weighting of the classes. The results in Table 2 show that a constant weighting function does not achieve the best accuracy. Trained the algorithm with a dynamic weighting function according to the amount of known devices improves the accuracy considerably. In this paper, a linear weighting function is used. This function has to be empirically verified as it has to be tested with any combination of the known devices. In these results the device combination was always static to facilitate the comparison between different weighting functions. For $f = 7$ in formula (3) almost all results reached a value close or equal to the best result achieved in Table 2. Thus a dynamic weighting function guarantees classification accuracy above 80% and therefore user acceptance [2].

Further result improvements

With further algorithm tuning the accuracy might be increased substantially. One way is to train the algorithm with different types and amounts of noise curves. This can be applied to noise itself and to any device that is trained even if it is a known or unknown device. With different noise on the raw measurement data the amount of samples can be artificially increased and therefore the weight of the single measurement decreased. This is a simple way to increase an algorithm's accuracy. Another way is to enlarge the training set of the unknown devices and to eliminate contradictory information. Heuristics could also improve the results as they base on experience and could consider e.g. a switched on application can't be turned on again or typically switch on duration or times could be considered.

Conclusion

The work presented in this paper describes our novel approach to better inform users about their household devices' energy consumption. We developed a NIALM algorithm which provides users with sufficiently detailed information about individual devices while guaranteeing high recognition accuracy. To recognize events where a device state changed, a two stage cascading machine learning approach is used.

In the first stage events are recognized and associated with predefined device classes. The associated information is communicated to the user. This first step can be integrated in NIALM systems by the manufacturers to help users understand their energy consumption at coarse detail.

In the second stage devices the user is specifically interested in are detected. The user has to train the NIALM system to recognize new devices of interest. This training information is added to the BFTree which achieves over 87% accuracy in our tests. We weighted the training data assuming there is a linear behaviour between the number of known devices and the weight of the unknown ones; i.e. the more connected devices the lower the weight for unknown devices. The achieved recognition rate can potentially be further increased with larger and more widespread training sets or by using heuristics. Our algorithm is able to output information as detailed as “Your Samsung Telestar MD 500 TV is switched on 4 hours a day” or “It is worth to replace your fridge with a more efficient one”. In sum we showed a way to provide users with accurate and more detailed information about their household devices' energy consumption.

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The effect of age on residential electricity demand: new evidence

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Abstract

Several determinants of residential energy demand have been studied extensively – including technical, economic, climatic and socio-demographic drivers. Fewer studies, however, have attempted to isolate the effect of age. We ask: do households with older members demand more or less electricity than those consisting of younger members when correcting this energy demand for other characteristics such as for example household size, living space, year of construction? This question has been at the core of a research project in Germany that has brought together household-level data on energy consumption, socio-demographic characteristics as well as building data, to measure the effect of age on residential energy demand for electricity. Whereas energy consumption data have been provided by three different municipal public utilities and housing companies, the remaining data have been collected during the German Census in 2011. The sample analyzed encompasses 6,163 single-person households. We find that, all else being equal, final electricity demand decreases by about 2.7 kWh per year of life. Consequently, an 80-year old person will, on average, consume about 135 kWh/year less electricity than a 30-year old person. The findings' robustness against potential outliers was validated through bootstrapping. Limitations to these findings include a relatively low explanatory power of the regression models, missing variables, non-random sampling, the restriction to single-person households and the use of cross-sectional data. Some of these limitations could be overcome in future research.

Introduction

This article explores the future role of electricity consumers in Germany and describes the influence of demographic change, in particular demographic ageing, on the final electricity demand of private households. In this context we examine the electricity consumption behavior of different age groups and whether households with older members demand more or less electricity than those consisting of younger members. While Germany's future energy consumers will not only decrease by number but also shift to an ageing society, answering this question is particularly relevant for the planning of long-life, capital-intensive energy supply systems. Over- or underestimating the future energy demand may involve considerable costs resulting from oversized or undersized energy infrastructure. With an ageing society, utility companies will need to plan their infrastructure accordingly. We start with a summary of the main results from previous research. These projects are considered in more detail within a literature review in [1, 2, 3]. Next, we present the data situation in Germany relating to micro-level socio-demographic analyses of energy consumption. As micro-level data analyses contain problems with regard to data security, a new method for data collection and analyses has been developed and will be described afterwards. The main part of this article outlines empirical evidence on the final electricity consumption behavior of different age groups in 6,163 German single-person households. The sample was collected in three Saxon cities of different size in 2010. Limitations to our research design and findings are discussed at the end of this article.

The connection between demographic ageing and residential energy demand

A review of the demographic development in all EU-28 member states shows that most of their populations are expected to age and shrink. In the case of Germany, both trends will occur at a relatively fast pace. Therefore, Germany's approach to demographic challenges may be a helpful example for other EU member states where demographic change will occur at a later date.

According to the latest population forecast of Germany's Federal Statistical Office, the population will decline from 81.8 million in 2010 to 64.6 million in 2060 [4]. Coevally, the proportion of young and elderly groups will change significantly because of low fertility rates since the 1970s and the baby-boom generations of the 1950s and 1960s reaching their retirement age. To illustrate this development, the age group of "65 and above" will increase from 20% in 2010 up to 34% in 2060 while the mean age will rise by 10 years, from 41 years in 2010 up to 51 years in 2060.

The three Saxon cities Leipzig, Chemnitz and Delitzsch (located in the county of Nordsachsen), taking part in our research project are all located in the former Eastern States where demographic change will occur very fast and with spatial disparity. According to the Saxon State Office of Statistics, the population in Leipzig will slightly increase (+1.5%) until 2030 while Chemnitz and Delitzsch will be confronted with a decline in population of -10.8% and -16% respectively [5].

In comparison to the German average, the population of Saxony will age faster and the mean age will increase from 45.9 years in 2009 up to about 50 years in 2025. This will be 3 years above the German average [6]. On the regional tier, the demographic ageing will occur in a heterogeneous way. Thus, the increase of the age group "80 and above" will be the highest in Dresden with +67%. However, Leipzig, Chemnitz and Nordsachsen will also be characterized by a high percentage increase of the elderly, expected to augment by +57%, +51% and +45% respectively (Figure 1).

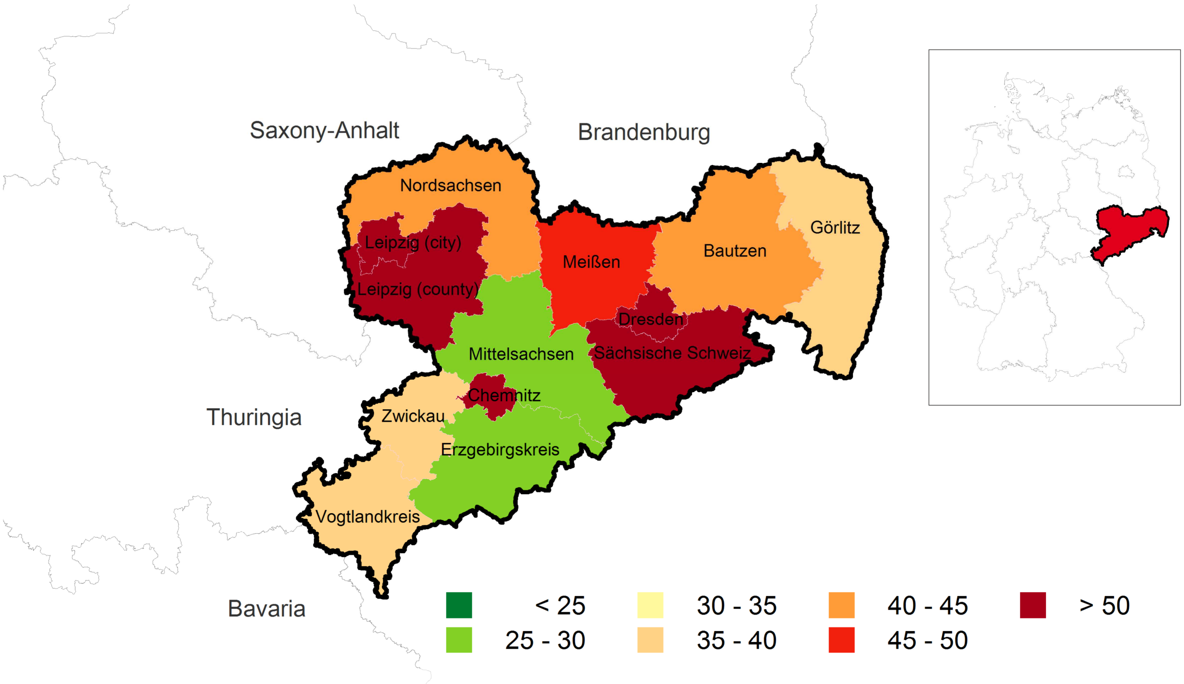

Figure 1: Increase of the age group "80 and above" in Saxony, 2009-2025 (%); Source [7]

Demographic ageing and residential energy demand may be connected in two ways. First, consumer behavior varies over the course of an individual's lifecycle. That is, different age groups demand age-specific goods and services, for example school books or baby food. Such a lifecycle effect could also be valid for energy goods. In the context of demographic ageing it is thus relevant whether the energy consumption of elderly people differs systematically from that of younger people and whether demographic ageing may be a push- or a pull-factor on residential energy demand (or whether it has no effect at all).

Second, demographic ageing forces the trend towards smaller households. As elderly people in Germany mostly live in single or 2-person households, demographic ageing may lead to a loss of household economies of scale in energy use [24, 25], i.e. a reduced sharing of appliances. Furthermore, demographic ageing affects the living space development and how today's housing stock will be inhabited by smaller households in the future. As a result, living space per capita rises.

Key findings of the literature review

Many research projects underline that a household's age has a significant influence on residential energy demand. Both German and international research projects provide some evidence that energy demand rises with an individual's age. However, the results lack a precise deduction of age-related consumer behavior. This may be explained by an interaction of several demographic and socio-economic household characteristics. For instance, it is difficult to disentangle whether and to what extent higher energy consumption is caused by factors like the household income of elderly people, their housing conditions or an age-related consumer behavior. The following paragraphs give an overview about the current state of research with regard to the question whether households with older members demand more or less energy than those consisting of younger members.

- **Age and household size:** As demographic ageing forces the trend towards smaller households in many industrial countries, several researchers analyzed the effect of the household size on households' energy demand. Researchers in Japan [8], the United States [9], several EU member states [10] and especially Germany [3] found that per capita residential energy demand rises within individuals' lifecycles. A frequently mentioned reason for this finding is that elderly people live in smaller households. Therefore, the loss of household economies of scale might be a reason [25]. Those effects result from a more efficient energy use in multi-person households by sharing appliances.

- **Housing situation of the elderly:** Some researchers came to the conclusion that the higher energy consumption of elderly households is caused by "remanence effects" – i.e. human inertia [11]. This term describes the situation when elderly people stay in the house which was originally built for the family, despite the loss of a partner or their children moving out once grown up. As a consequence, per capita living space rises with people's age; and the higher energy demand of elderly households may be an outcome of an increasing living space per capita. Another reason may be the living in a rather old and less energy-efficient housing stock [8, 12, 13].

- **Age and household income:** As both household income and therefore living space increase within individuals' lifecycles, many researchers associate the higher energy demand of elderly people with the increase of household income [15, 18, 3]. Research in Japan points out that a low income also acts as a negative contributor to energy consumption ~~b~~ut found the income effect to be rather limited [8].

- **Age-related consumer behavior:** Some studies attribute the higher energy demand of elderly households to behavioral aspects. Some researchers found them to prefer higher room temperatures for space heating [8, 14]. Another reason may be that they simply spend more time at home which, in turn, leads to more utilization hours of heating and appliances [15, 14, 16, 17].

To sum up, the literature review indicates that households' age may have a significant influence on residential energy demand. The increasing energy demand within people's lifecycles is mainly attributed to the fact that older households feature characteristics which are push-factors with respect to residential energy demand, whereas younger households feature characteristics which are pull-factors. Elderly households tend to be small in size (i.e. with little potential for economies of scale), occupy large dwellings and have therefore a high living space per capita (remanence effects). In the case of Germany, they currently have an above-average income [3]. However, some findings also indicate age-related consumption behavior.

Given the limitations of prior research on the determinants of residential energy demand, we have developed a new method for better correlating data on energy consumption, housing situation and inhabitants' demographics. The application of this method needed considerable data collection efforts, as those three different types of data are usually dispersed across different sources such as building or apartment owners, public municipalities and registration offices (for details on the method, see [1, 5]).

Method

Data sources and collection

The data was gathered by Prognos AG and AGFW (the German District Heating Association) within the project "Urban restructuring and energy efficiency", commissioned by the Saxon State Ministry of Interior Affairs [26]. As data sources, we relied on housing companies and municipal public utilities in the cities of Chemnitz, Delitzsch and Leipzig, as well as on the Saxon State Office of Statistics.

The municipal public utilities provided metered data on electricity consumption for individual grid connections, and the housing companies delivered data on the state of redevelopment of a building.

The statistical office provided information on further buildings characteristics and socio-demographic data of the inhabitants it had collected during the German Census 2011 [19, 20, 21].

To match those different kinds of data, the statistical office applied a special data-processing procedure for “household generation” that had been developed in the context of the German Census 2011 [1; 19]. At the end of this four-tiered procedure, all individuals who live at a given address are matched with a household and a dwelling.

The resulting data set contained socio-demographic characteristics as well as households’ electricity consumption, and further housing data such as living space surface and year of construction. For reasons of privacy protection, this comprehensive data set never left the statistical office. Instead, we sent the statistical program code to the office, and the office performed the respective analyses on our account.

Data preparation

After the statistical office had consolidated the data from the distinct sources described above, we obtained the observations shown in table 4 below, which stemmed exclusively from tenants in multi-family houses. In order to increase the overall sample size for the subsequent analyses, we combined the data from the three cities. Out of the total of 11,567 observations, 6,373 were single-person households (~55%). This percentage may not be representative for the share of single-person households in all German households, but it is nevertheless not uncommon to observe such percentages in German cities.

By means of a boxplot analysis of electricity consumption, we identified outliers. Observations qualified as outliers if their electricity consumption was outside 1.5 times the interquartile range of the total data set related to Chemnitz, Delitzsch and Leipzig cities. After removing the outliers, we were left with a total of 6,163 observations.

All analyses below refer to the remaining dataset with single-person households in multi-family houses without outliers. Such special focus is necessary for isolating the age effect of interest as much as possible. Conversely, we would not know how to alternatively operationalize the concept of “household age” for multi-person households – in which people at very different ages can live together. For example, a 60-year old person may live with a 20-year old person, leading to an average household age of 40 years. This would not be distinguishable from the average household age of a household consisting of, e.g., a 50-year old person and a 30-year old person, or of two 40-year old persons. These examples illustrate that there is no one-to-one relationship between average household age and the age of individual household members, which would confound the attribution of aggregated household behavior, such as electricity consumption, to the age of individual household members. Therefore, we have restricted our analysis to single-person households.

Table 4: Number of observations

Number of observations	**Chemnitz**	**Delitzsch**	**Leipzig**	**Total**
All households	2,819	1,510	7,238	11,567
Thereof: Single-person households	1,140	821	4,412	6,373
Thereof: outliers	46	16	148	210
Remaining dataset for subsequent analysis	**1,094**	**805**	**4,264**	**6,163**

Source: [5]

The process of data preparation also encompassed calculating per-capita electricity consumption, that is, household consumption divided by the number of household members. Table 5 exhibits the variables analyzed with their dimensions by data category and associated data sources.

Table 5: Variables analyzed

Data category	Variable	Dimension / categories	Data source
Consumption in 2010	Electricity consumption	kWh/a	Municipal public utilities
Building	State of redevelopment	Categories: not refurbished, partially refurbished, completely refurbished, new	Housing companies
	Year of construction	-	Statistical Office (German Census 2011)
Apartment	Living space	m²	
Demography	Number of household members	-	
	Age	-	

Source: [5]

Approaches to data analysis

The resulting dataset with cross-sectional data was examined by means of bivariate and multivariate approaches.

Bivariate analyses encompassed contrasting two variables with each other. For example, we showed consumption over age – both continuously and by age groups of selected generations. For example, we looked specifically at the age group “30 and under” which is projected to decline heavily, and at the group “80 and older” which will show the strongest increase. Additional analyses included living space and building age.

Multivariate analyses were performed by applying linear multiple regression models in the following form:

$$Consumption = \alpha + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + u$$

with *Consumption* – electricity consumption per capita;
α – intercept;
β_k – coefficient of the independent variable X_k;
u – error term

Electricity consumption represented the dependent variable, to model the influence of the independent variables from the three categories buildings, apartments and demography (as shown in table 5 above).

The models were estimated by means of ordinary least squares. In addition, we performed bootstrapping [22, 23] with 2,000 replications to make the variability of results visible and to minimize the effect of any potentially remaining outliers in the dataset.

Results

Descriptive statistics

Table 6 shows descriptive statistics of the key variables electricity consumption, age, year of construction and living space. Even though outliers have already been removed by means of a boxplot analysis as described above, electricity consumption per capita has a minimum of 1 kWh/a which does not seem to be a realistic value even for a single-person households with very low consumption.

Table 6: Descriptive statistics of key variables

Variable	Mean	Median	SD	Min	Max
Electricity consumption per capita	1,050	1,015	427	1	2,244

(kWh/a)					
Age*	61.6	64	18.7	18	102
Year of construction*	1969	1975	20	1900	2004
Living space (m²)*	48.7	48	12.1	22	152

Source: [5]

* Note: This variable refers to a more encompassing dataset with 10,490 observations which includes the subset of 6,163 observations for electricity consumption per capita.

Figure 1 exhibits histograms for electricity consumption per capita and age.

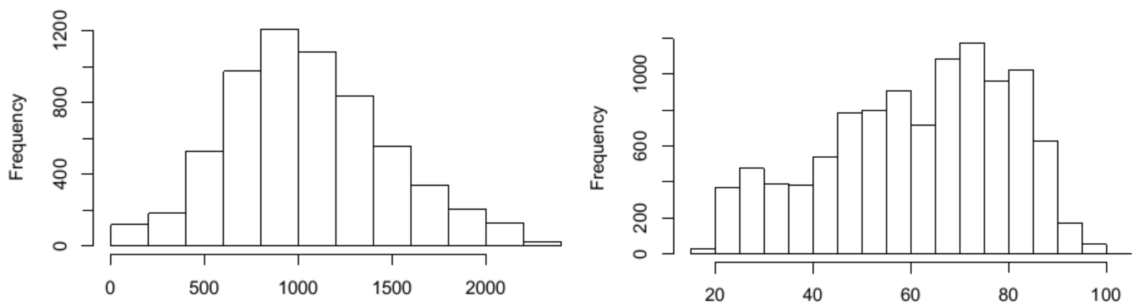

Figure 1: Histogram of electricity consumption in kWh/year (left panel) and of age (right panel)

Source: [5]

Figure 2 exhibits electricity consumption of single-person households by age (A) groups. No easy pattern is visible. The highest electricity consumption occurs in the age group “50 to 64” years, the lowest consumption in the group “80 and older”. When comparing youngest and oldest age groups, we see a reduction in consumption from 1,059 kWh/a (“30 and under”) to 1,005 kWh/a (“80 and older”), representing a decline of about 5%.

This simple comparison of means by age groups, however, may tend to underestimate the effect of age on electricity consumption, because other determinants such as living space have not been integrated into the analysis yet. To account for such other variables, we perform a multivariate analysis.

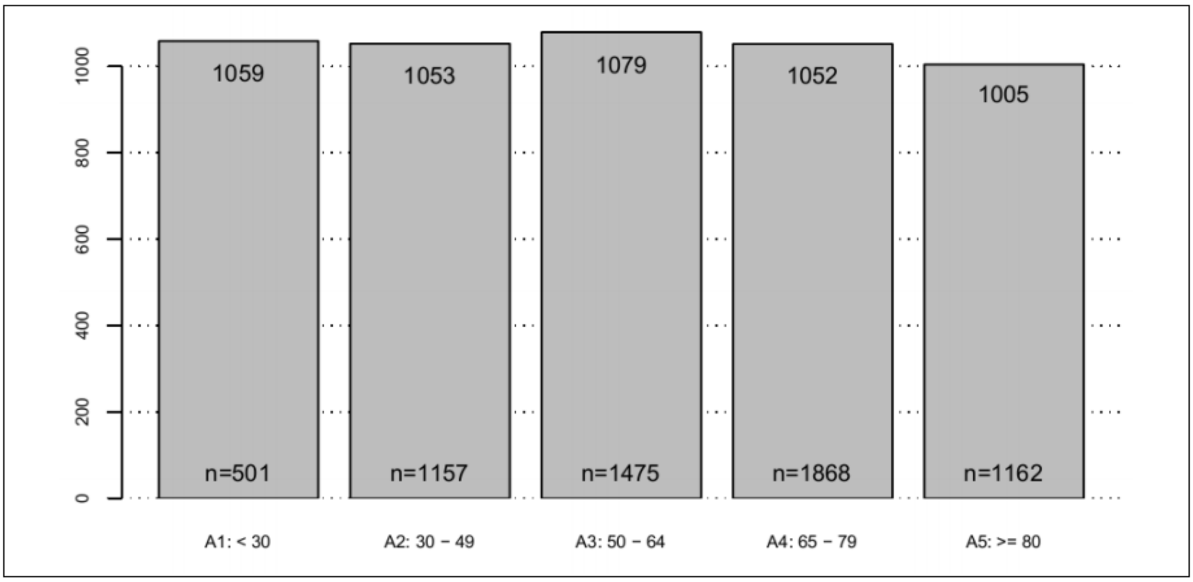

Figure 2: Electricity consumption of single-person households by age (A) groups in kWh/a

Source: [5]

Multivariate results

Table 6 shows the regression results for models (1) to (4), with electricity consumption per capita as the dependent variable. All models include the independent variable age because the effect of age on electricity consumption is of primary interest in this article. The models also include living space because the larger an apartment, the more electricity-consuming applications can be used.

As additional independent variables,

- models (2) to (4) include the *year of construction of the building* to account for the possibility that the age of a building has an effect on electricity consumption;
- models (3) and (4) include dummy variables for the *state of redevelopment* to account for the possibility that redevelopment may explain some of the variance in electricity consumption.
- model (4) includes dummy variables for the *cities* to allow for the possibility that electricity consumption in the cities may differ systematically. Moreover, model (4) includes a dummy variable for single-person households *older than 60 years* to account for a specific impact of the aged.

For the variables age, living space and year of construction, the estimated coefficients are statistically significant at a level of 1% in all models. The same is true for the constant.

All other variables included in models (3) and (4) are not statistically significant at a level of 5% when considered individually. However, when comparing model (4) with model (1), an F-Test reveals that the hypothesis that model (4) does *not* provide a significantly better fit than model (1) can be *rejected* at a level of 0.1%. Still, relative to model (1) with an adjusted R^2 of 0.088, model (4) only increases the adjusted R^2 to 0.092.

Table 6: Regressions results for electricity consumption per capita

	Dependent variable: Electricity consumption per capita			
	(1)	(2)	(3)	(4)
Age	−2.324***	−2.340***	−2.409***	−2.715***
	(0.285)	*(0.284)*	*(0.285)*	*(0.605)*
Living space	10.941***	11.280***	11.315***	11.321***
	(0.450)	*(0.457)*	*(0.459)*	*(0.462)*
Year of construction		1.126***	1.590***	1.592***
		(0.271)	*(0.298)*	*(0.312)*
State of redevelopment dummy 2			11.902	11.765
			(49.801)	*(50.314)*
State of redevelopment dummy 3			−38.827	−38.713
			(49.595)	*(49.775)*
Delitzsch city dummy				1.487
				(19.673)
Leipzig city dummy				0.557
				(14.068)
Age > 60 yrs				0.170
				(0.295)
Constant	662.692***	−1,571.302***	−2,478.199***	−2,471.194***
	(25.289)	*(538.654)*	*(600.991)*	*(630.969)*
Observations	6,163	6,163	6,163	6,163
R2	0.088	0.091	0.094	0.094
Adjusted R2	0.088	0.091	0.093	0.092
Residual Std. Error	407432	406896	406384	406472
	(df=6160)	(df=6159)	(df=6157)	(df=6154)
F Statistic	299.033***	205.627***	127.191***	79.502***
	(df =2; 6160)	(df=3; 6159)	(df=5; 6157)	(df=8;6154)

*Note: Standard errors in parentheses; *p<0.1; **p<0.05; ***p<0.01*

Source: [5]

To assess the robustness of model (4), we constructed 95% bootstrap confidence intervals for the estimated regressions coefficient of age based on 2,000 replications. This robustness was especially important, given the implausible minimum electricity consumption of 1 kWh/a (see table 6 above). Table 7 below shows three different types of bootstrap confidence intervals [23].

Table 7: 95% bootstrap confidence intervals for the estimated age coefficient in model (4)

Bootstrap confidence interval type	Left boundary	Right boundary
Normal	-3.980	-1.432
Basic	-3.961	-1.402
Percentile	-4.027	-1.468

Source: [5]

Discussion

A critical appraisal of our results needs to include the sign, size and significance of the age effect, as well as some other considerations.

1. When comparing our result with the literature, we find that it conflicts with other studies that have indicated a rather increasing electricity demand with age [16, 17]. On the one hand, older people may in fact spend more time at home, implying higher utilization of appliances. On the other hand, a decline in electricity consumption with age might be explained in part by a different use of information and communication technologies. Today, older individuals do not use the internet as much as younger ones and they can be assumed to own fewer electricity-consuming internet devices. This difference, however, may get smaller in the future, especially if a generation with a high propensity to consume will keep its behavior at higher age.

Generalizing our findings to other contexts needs to take into account the specific setting of our research: We have analyzed residential electricity consumption of households that did not use electricity for heating. This is similar to Germany overall, where electricity use for heating purposes is negligible. In other countries, however, electricity for heating (or cooling) may play a more important role. Under those conditions, it would be more difficult to disentangle the effect of age on electricity demand from the effect of age on heating demand (see literature review). Therefore, our finding is limited to households in countries where electricity is not important for heating.

2. The substantial size of the estimated coefficient for age can be interpreted as follows: an increase in age by one year is – on average – associated with a decrease in per-capita electricity consumption of about 2.7 kWh per year. This result implies that an 80-year old individual would, on average, consume about 135 kWh less per year than a 30-year old individual. In other words, the reduction in energy consumption between the two age groups would be about 13% - which is more than the 5% described above as descriptive statistics.

3. When trying to interpret the statistical significance of our findings, we have to keep the following in mind: The data were gathered as part of a convenience sample. The key criterion for selection was actual availability for the participating partners. Therefore, only tenant households in multi-family houses were involved. Single-family houses were not part of the data collection process. As long as the households in the sample do not systematically deviate from households outside of the sample differ, it should be possible to transfer the results obtained here to other households. This transferability, however, cannot be validated completely, as – in addition to observable attributes such as socio-demographics – unobservable attributes such as individual consumer behavior may also play in a role. The convenience sample used in this analysis is not a random sample. Therefore, conventional statistical tests for inference and for generalizing the results to a larger population cannot be applied.

4. The predominant part of the variance in the data on electricity consumption cannot be explained statistically, as expressed by the low R^2. That is, there are other confounding factors that could not be analyzed here. They may include – among others – income, unemployment, actual presence in one's apartment. Especially the latter, however, is usually very hard to measure. Moreover, individual consumer behavior based on beliefs or attitudes might explain an important part of the consumption effect.

5. Compared to other projects conducted in the past, our sample is relatively large. This makes it rather plausible that we have covered a somewhat large spectrum of types of households. Moreover, our estimates are robust, as demonstrated through bootstrapping, and expressed in the bootstrap confidence intervals.

6. We have analyzed only single-person households because only for them were we able to operationalize the concept of "household age". We cannot answer the question how to generalize our results to multi-person households.

7. Our analysis builds on cross-section data for the year 2010. As not longitudinal data is available, we cannot observe change in individual behavior over time. This leads to the question how transferable our results are to individuals at future points in time. In other words, will the current

generation of mid-age (50 to 64 years old) which is said to have a high propensity to consumer keep this propensity at a higher age?

Future research

Given the preceding discussion, future research on the effect of age on electricity consumption should focus on

- integrating further variables such as income, unemployment and actual presence in one's apartment
- drawing a random sample
- examining the transferability to multi-person households
- validating the results with time series data.

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Household refrigerators: Monitoring efficiency changes in Europe and Australia over the last 10 years

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Abstract

Sales data gathered by a commercial market monitoring agency includes information regarding energy efficiency and consumption, size and price and thus has allowed detailed tracking of trends in household refrigerator characteristics in Australia and Europe for over ten years.

For Europe, GfK sales data from 2004 – 2014 has been analysed in this paper. For Australia, more detailed sales data has been available over a much longer time period (1993 – 2014), so this provides a useful comparison with the European trends. As a result of mandatory product registration, the sales information by model in Australia can be complemented with comprehensive product details to allow tracking of all key features.

For household refrigerators, this paper analyses market trends in energy efficiency, absolute energy consumption, size and price in Europe and Australia; examines the impact and timing of regional policies, including MEPS and energy labelling; proposes explanations for patterns observed; compares and contrasts the Australian and European trends and context, allowing the two regions to learn from previous policy approaches, and makes recommendations regarding MEPS and energy labelling, as well as market monitoring and product registration.

Background

Energy Labels and minimum energy performance standards (MEPS) for energy using products are crucial policy instruments that support on-going market transformation towards higher energy efficiency and lower energy consumption. Appropriate levels for Energy Label classes and their relationship with MEPS levels are key for the effectiveness of these policy instruments: if most models are already in the best Label class and no challenging MEPS are implemented, innovation can stall (see examples dishwashers or ovens in [1]). Label efficiency classes that are still beyond the current market generate market pull while challenging MEPS levels push poor performing products to a higher efficiency level. Together, these instruments ensure that the efficiency of products is improving continuously (example refrigerators and freezers in [1]).

To ensure that policy measures are effective, it is critical to understand the market in terms of what products are sold and their attributes (including efficiency). Understanding the market empowers policy makers to make orderly and well informed decisions about the optimal level for new MEPS and Energy Label class limits and their timing in order to achieve maximum effectiveness. If sales data are available over a longer period, it is possible to develop stock models to estimate trends in energy consumption and other attributes [2] – this can be used for assessing past savings from previous policies as well as projecting future savings from proposed new policies (see [3] for an example). A database containing all models that are on the market can also support ongoing market surveillance – it facilitates selection of models for compliance tests and can show all similar models belonging to the same ‘model family’ for which the test results are applicable.

Australia: Label re-grades are based on systematic market monitoring

Since energy labelling commenced in 1986, Australia has had a mandatory product registration system for all products that are covered by Energy Labelling and MEPS. Initially this was administered at a state level, but is now national. New Zealand introduced mandatory regulations for product energy efficiency in 2002 and shares the same registration system and program requirements for nearly all products. Each model that is put on the market has to be registered with its energy specifications. Many other important economies have similar product registration systems: e.g. Brazil, Canada, China, India and the USA [4]. The Australian product registration database has a public component that is used to inform consumers about energy saving products: An app for mobile phones as well as a website listing allows consumers to see all products on the market sorted by efficiency (or any other attribute) as well as the operating cost (energy cost over the product lifetime) of any model [5]. At the same time, the government uses the data for assessments when revising MEPS and Energy Labels. In addition, the Australian government has been monitoring the market for whitegoods with sales data purchased from GfK from 1993 to 2014 [3]. In New Zealand, suppliers are required to provide sales data for each model annually. The NZ government publishes a report with aggregated data, including energy and efficiency trends as well as energy savings [4].

In Australia and New Zealand, the energy label for refrigerators and freezers was re-graded in 2000 and again in 2010. In 2010 the scale was shifted so that the stars earned for most products were reduced by two stars and the number of available stars was increased to 10 stars. At this stage no products on the market earn more than five stars. MEPS levels were first introduced in 1999 (the same year as in Europe) and were upgraded in 2005 (to broadly align with US 2001 MEPS levels). Regulatory proposals to adopt US 2014 MEPS levels in 2018 are under development [6]. The energy labelling system will be upgraded again in parallel with the introduction of this new MEPS level. One of the important aspects will be the use of the recently published IEC62552-3 [7] with energy measurements at two ambient temperatures to determine the product energy consumption, so this can more closely match normal use.

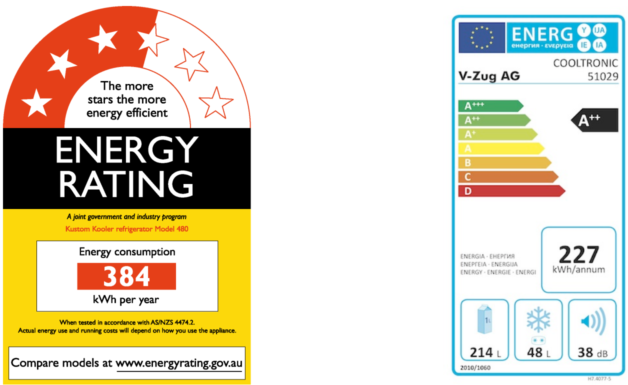

Figure 1: Australian and European Refrigerator Energy Labels, both from 2010

Note that the energy values are not directly comparable due to different sizes and test methods.

Europe: lack of market data can lead to suboptimal policies

Europe has no systematic market monitoring system: there is no product registration requirement, and no sales data are purchased, analysed and published on a systematic basis. Little is known about the market developments and the effect of past policies. Whenever market information is needed for a policy preparatory study or an impact assessment, available data is gathered by consultants. The data, which is usually provided by industry, is often incomplete and out-of-date and the different datasets cannot be directly compared over time and between countries. As a consequence, some Ecodesign and Energy Label requirements may have been designed at sub-optimal levels and energy saving opportunities may have been missed. Several of the Energy Labels recently introduced have required revision shortly after their introduction to the market: many products are already in the top-A+++-classes of the new Labels for washing machines, dishwashers, and tumble driers[1]. The Evaluation study of the Energy Labelling Directive [8] recommended that Europe should establish a product registration database to facilitate market surveillance and data collection for preparatory study market analysis.

The original EU refrigerator and freezer Energy Label, introduced in 1995, has never been re-scaled. Instead the original A-G scale was amended with the addition of new classes A+ and A++ in 2004 and A+++ in 2011. MEPS banned label classes D, E and F in 1999, B and C in 2010 and finally A in two

[1] Easily visible on the lists of most energy efficient products on www.topten.eu

steps: 2012/2014. Currently a revision of the current Ecodesign and Energy Labelling regulations for household refrigerators and freezers ([9] and [10]) is in preparation.

European and Australian refrigerator markets

Few current details are known about the European refrigerator market. The preparatory study from 2007 concluded that it was saturated with ownership at one appliance per household and a stock energy consumption of 82 TWh/year for the EU-27 [11]. The Energy Efficiency Status report from 2012 [12] presents some partial GfK sales data from Austria and Italy and price information from ten EU countries. An EU mapping and benchmarking report from 2012 [13] reports on average refrigerator and freezer volume (205l / 75l) and annual energy consumption (288 kWh/year in 2011), based on GfK sales data up to 2011 from 14 EU countries.

For Australia past reports have described the market trends. The ‘Greening Whitegoods’ report [14] analyzed sales data from 1993 to 2009 and found that between 1993 and 2009 the sales weighted energy consumption was trending downward at -2.9% per year for the entire period. In 2009 the average annual energy consumption was 480 kWh. The impact of the MEPS levels announced for 2005 is clearly visible: just prior to the implementation, energy consumption fell considerably below the long term trends.

Analysis undertaken in 2012 estimates that adoption of new MEPS levels in Australia and New Zealand in around 2018 will result in a further 30% reduction in energy over a 3 year period [6], depending on the implementation date.

Paper objectives

This paper aims to support the revision process of the refrigerator Energy Label and Ecodesign regulations in Europe with solid, current market data that allows evaluation of the impact of policies in the past. It also demonstrates the potential of information obtained from systematic market monitoring. This potential is underlined by the case study from Australia, where a near-perfect combination of sales and model registration data provides precise information on the market over time.

Data and Methods

Europe

Thanks to funds from the WWF Switzerland [15], the Topten study team was able to purchase refrigerators sales data from GfK [16], a professional market analysis company that operates in many countries around the world. In Europe, GfK covers around 90% of the refrigerator market, and all 28 Member States. Sales data, together with many product characteristics, are obtained by GfK from retailers.

The data obtained for this paper covers refrigerators with and without a freezer compartment for the years 2004 – 2014 and has been aggregated for 21 EU countries[2]. Separate freezers are not included. For each Energy Class (A+++ to G) GfK provided sales and sales weighted values for average price, energy consumption, and refrigerator and freezer volume. In addition, for France and Portugal, the same information was obtained at a country level, thanks to funding by Ademe [17], the French Environment and Energy Management Agency.

A full report [18], including analysis of data for washing machines and tumble driers, is available from www.topten.eu.

Australia

In Australia all refrigerator models must be registered with government when they are placed on the market. A public component of this registration database provides technical information on each current model. The government holds a long term database of all registrations ever submitted (nearly

[2] AT, BE, CZ, DE, DK, ES, FI, FR, GB, GR, HR, HU, IE, IT, NL, PL, PT, RO, SE, SI, SK.

30 years). Data from the products database can be combined with GfK model level sales data to provide highly accurate tracking of sales weighted characteristics of the market for each year. This Australian approach is the gold standard in market monitoring.

Energy and efficiency comparisons between Australia and Europe have to be interpreted with caution. The declarations are based on different test methods in the two regions – e.g. Australian and NZ models are tested at a higher ambient temperature than European refrigerators.

Results and discussion

Europe

The number of refrigerator units sold remained more or less stable in the 21 EU countries that have been included in the analysis. Over the last then years the annual sales fluctuated between 14.3 million (2009) and 15.6 million units (2006/2007). In 2014, 14.9 million units were sold [18].

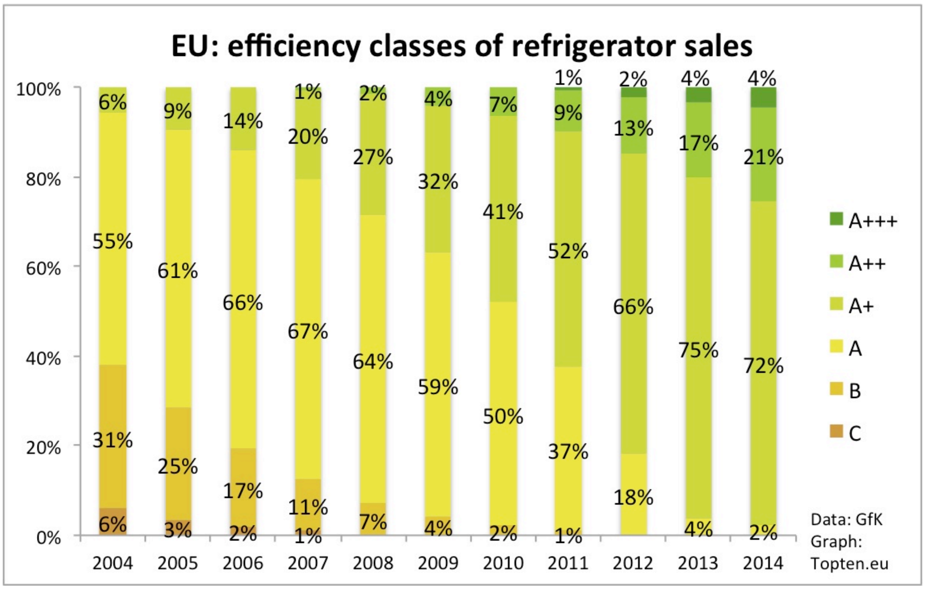

Figure 2: The EU market has improved by more than one efficiency class in 10 years

Figure 2 shows continuous improvements in refrigerator efficiency from 2004 to 2014. The average efficiency index has improved by 34% in this period (Average EEI 2014: 39)[3].

Table 1: Energy Efficiency Index (EEI) of Label classes

Class	Max. EEI 2004 - 2011	Max. EEI since 2012
A+++		22
A++	30	33
A+	42	42*
A	55	55
B	75	75
C	90	95

Label classes according to [10, 19, 20]. *The A+ EEI was temporarily increased to 44 from December 2011 until July 2014. This was related to the measurement tolerance being lowered at the same time.

In 2004 classes A and B dominated the market. New, better classes were required, and class A+ quickly gained market share after its introduction in 2004. Ten years later this label class is dominating the market. Classes B and C had both virtually disappeared from the market before they were banned in 2010. The Ecodesign regulation from 2009 had a stronger effect: the disappearance

[3] Average EEI was calculated by assigning the maximum EEI to each class.

of class A was visibly accelerated by a MEPS level of A+ effectively applying from July 2012 . A++ is slowly gaining market share, A+++ appears to be following a similar trend.

Data from France and Portugal shows that these trends can vary between EU countries [18] – despite identical legislation: in these countries A+ dominated the 2014 sales, but A++ sales only accounted for 11% (France) and 12% (Portugal), which is below the EU average of 21%. A different picture can be clearly seen in Switzerland, where A+ cold appliances have been banned since 2013: in 2014, A++ sales accounted for nearly 80% of the total Swiss refrigerator sales [1].

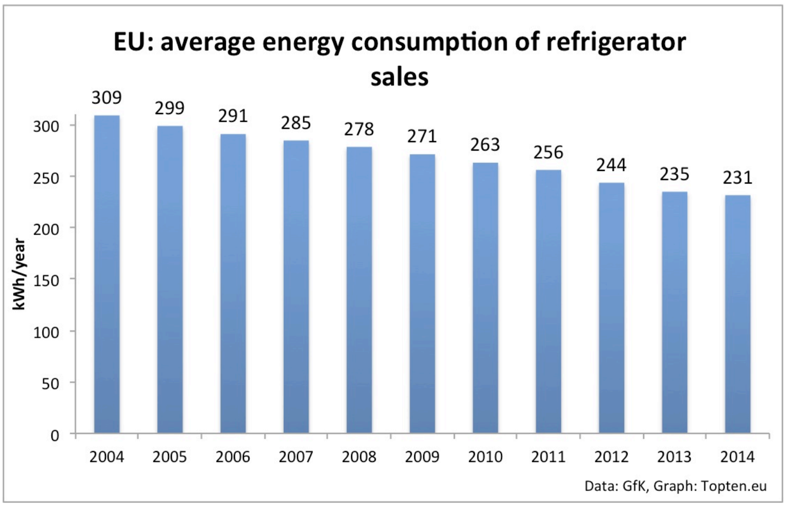

Figure 3: Average energy consumption has decreased by 78 kWh/year (25%)

Figure 3 illustrates that the market response to the Energy Label and MEPS policies, driven by industry innovation, has had the desired effect: average energy consumption has constantly been decreasing over the last ten years. The energy reduction of 25% down to an average declared energy value of 231 kWh/year is significant. The volumetric efficiency (kWh/l) improved by 27% over the period. However, the savings are smaller than the 34% improvement in the efficiency index shown in Figure 2. The difference cannot be explained by increased volume (Figure 4). Instead, the deviation is likely to be caused by factors that are not shown explicitly on the Energy Label: the current efficiency definition grants credits for certain special features such as a Frost Free function, built-in appliances, compressors that are rated for tropical climates, or a chill compartment. Since the European EEI formula rewards these features, it is probable that they have become more common. Another misleading aspect of the EEI formula is that different reference lines are used for different categories, making it much more difficult for refrigerators without freezer compartment to reach good efficiency levels than for refrigerator-freezers. A shift to a higher share of refrigerator-freezers is also likely to have contributed to the energy consumption reduction being lower than the gains in the label efficiency index.

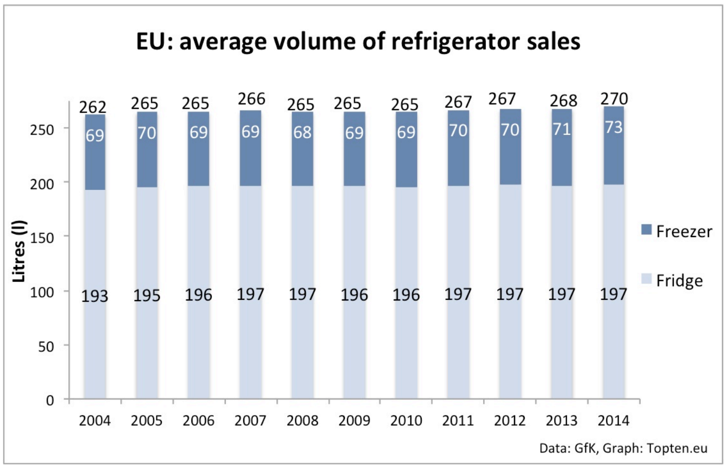

Figure 4: Total volume has increased by 8 litres (3%), the Freezer compartment by 4l (5%)

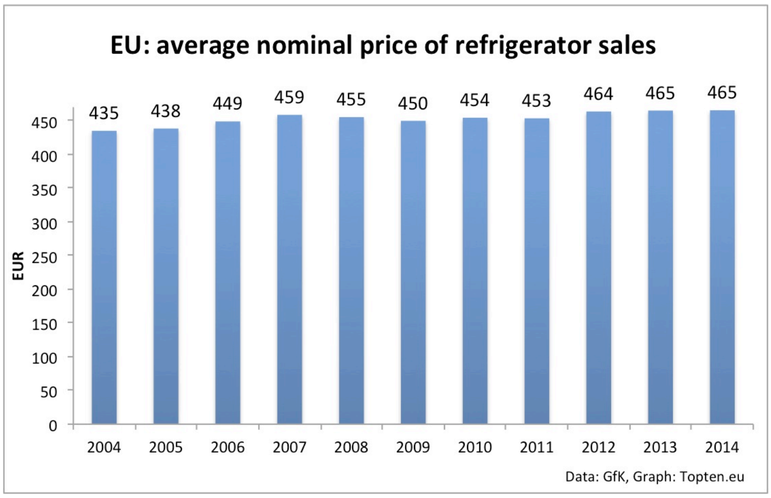

Figure 5: Average nominal price has increased by EUR 30 (7%)

While efficiency improved by 34%, the average nominal price paid for refrigerators only increased by 7% over the same period. Total lifecycle costs for consumers, based on the average price and declared energy consumption, were reduced by 13% from EUR 1130 in 2004 to EUR 985 in 2014[4].

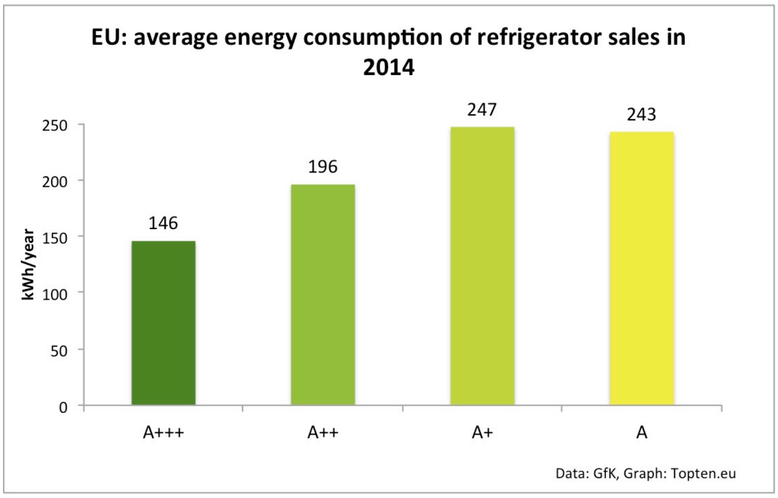

Figure 6: A+++ refrigerators save > 40% energy over A+ refrigerators, A++ > 20%

Energy consumption differences between efficiency classes are large for refrigerators: a move from A+ to A++ saves 21% electricity, a move from A+ to A+++ is a 41% reduction. While the consumption difference between A+ and A++ reflects exactly the EEI difference between the two classes (Table 1), the EEI difference is a bit larger (48%) from A+ to A+++ than the reduction in energy consumption from the sales weighted analysis. Analysis of the average volume per class shows that the reason for this difference is likely the larger volume of A+++ refrigerators: total volume of A+++ refrigerators was 15% larger than of A+ models (freezer compartment: +17%) [18]. Still, the gains in efficiency clearly outweigh the effect of the larger volume on energy consumption.

Higher efficiency of refrigerators delivers a large electricity saving potential for Europe. A move from the 2014 average efficiency (EEI=39) to A++ would lead to 15% energy savings – over the entire lifetime of the appliances that are sold in a specific year. Based on annual sales and average annual energy consumption, these savings amount to 7.8 TWh for one year of sales (or annual stock savings

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[4] Assumptions: 15 years of lifetime, energy cost of 0.15 Euro/kWh.

if the entire stock was replaced)[5]. An estimate, which included separate freezers in this calculation, results in nearly 10 TWh of annual savings. These savings could have been hypothetically obtained with the 2014 sales, if the minimum efficiency requirement had been moved to A++ (the Swiss MEPS level).

Australia

The number of refrigerator units sold in Australia has been stable for around 10 years at close to 1 million units per annum [14].

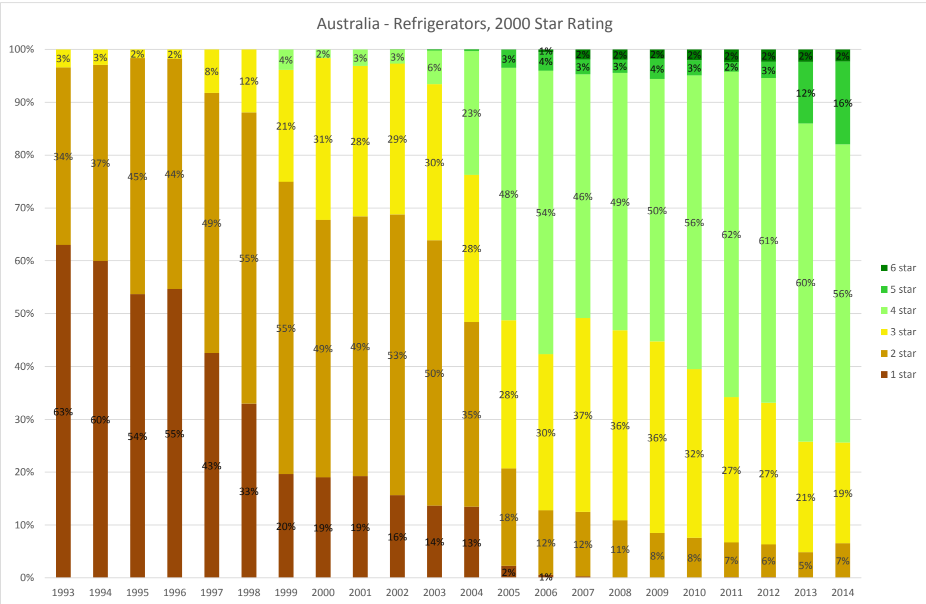

Figure 7: Refrigerator sales from 1993-2014, according to the star rating from 2000

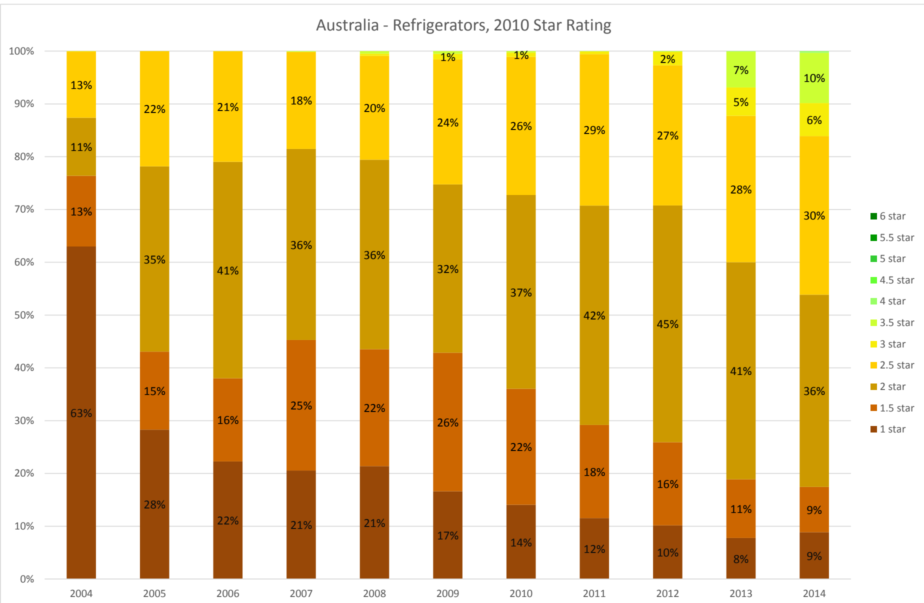

Figure 8: Refrigerator sales from 2004 to 2014, according to the star rating from 2010

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[5] We project the lifetime savings of the appliances by their year of sale. It is a simpler approach than estimating the savings if the entire stock was replaced, but this approaches the figure of annual stock savings (after full replacement). Assumed lifetime was 15 years. Freezer sales were estimated at 25% of refrigerator sales, based on [1].

Figure 7 shows the share by star rating for refrigerators during the period 1993 to 2014 in accordance with the star rating equations implemented in 2000. This rating system applied to the market from 2000 to 2010 so will be the period where it had most effect. Some obvious step changes in efficiency improvements are apparent around the introduction of new MEPS levels in 1999 and 2005. Figure 8 is equivalent for the period 2004 to 2014 in accordance with the star rating equations applied to the market from 2010. The rate of change from energy labelling slowed for several years after the introduction of stringent MEPS levels in 2005, which is expected to some extent. However, the effect of the energy label after 2005 was also diminished as most products were rated at 4 or 5 stars under the 2000 algorithm that applied at the time, which is perceived as high (or at least acceptable) efficiency by consumers in Australia. Since 2010, after the introduction of the newly re-graded star rating, the rate of improvement in star rating has increased visibly, suggesting that re-grading the label classes do result in increased market pull.

In Australia, the energy labelling classes (or thresholds) are defined relative to the Base Energy Consumption, or the 1 star line. For refrigerators, a 23% reduction in energy is required for each additional star earned for all star ratings. The relative size of each class is therefore uniform for all classes, but the actual kWh decrease per star becomes smaller as the total energy decreases, reflecting the fact that each extra kWh is more difficult to save as the total energy reduces. Intermediate classes of half stars are also shown in the label.

Table 2: **Energy requirements for refrigerator label classes in Australia and New Zealand (2010 star rating algorithm)**

Label class	Max. energy compared to reference 1 star
6 star	27.1%
5.5 star	30.8%
5 star	35.2%
4.5 star	40.1%
4 star	45.7%
3.5 star	52.0%
3 star	59.3%
2.5 star	67.6%
2 star	77.0%
1.5 star	87.7%
1 star	100.0%

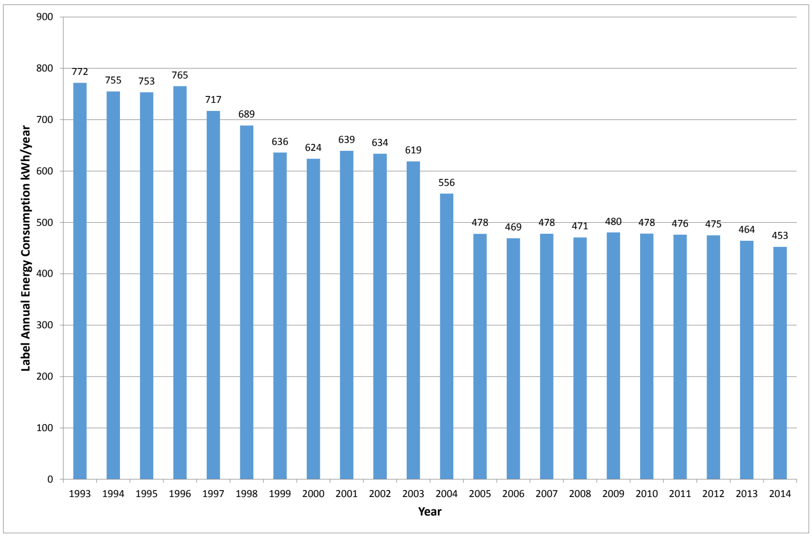

Figure 9: Change in annual energy consumption of refrigerators in Australia

New MEPS levels were introduced in Australia in 1999 and 2005. The impact of these is clearly visible in Figure 9. For some years after a new MEPS level the background rate of improvement appears to slow. The 2.9% annual improvement shown in [14| has decreased to about 1% after 2009. Average size of products increased by 23% during the 20 year period where data is available (Figure 10), while energy reduced by 41%. This equates to a volumetric efficiency improvement of 52% over 20 years. Energy savings from 2002 to 2014 are around 30% (looking at the period 2004-2014 would tend to understate the energy reduction because most of the MEPS 2005 saving were achieved by 2004). An evaluation of MEPS and labelling impacts in 2010 found that the energy savings from labelling and MEPS were greater than predicted in the original studies conducted prior to each of these MEPS regulations [3].

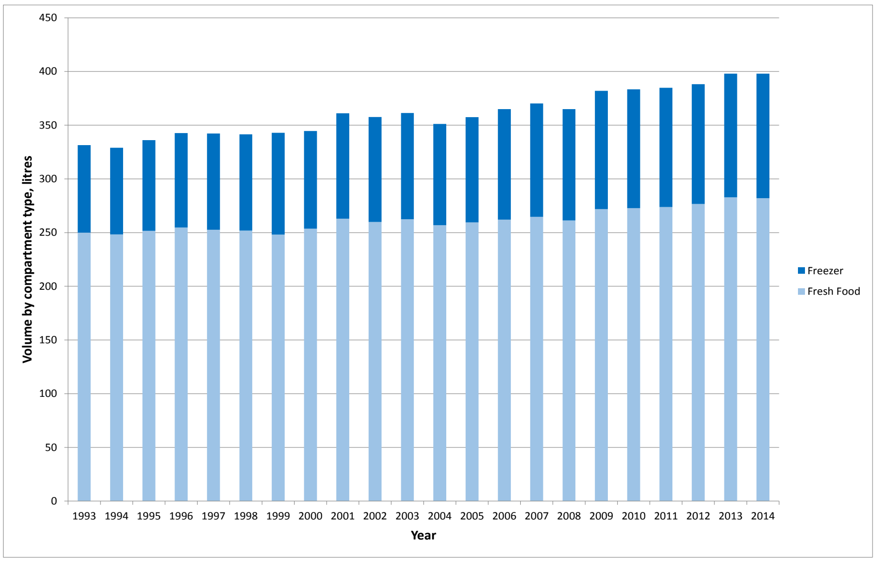

Figure 10: Changes in compartment volume over time in Australia

The size of refrigerating appliances sold in Australia has been increasing slowly for many years. Over a period that is comparable to the European data (2004 to 2014), total size has increased by 13% (compared to 3% for Europe).

Nominal prices paid for products in Australia have been fairly stable for many years, despite the increasing share of larger appliances with more features, such as automatic defrost (which is now almost universal for most product types). Real prices, corrected for changes in inflation, have decreased by 35% over the past 20 years. This is a feature that is common in many markets around the world.

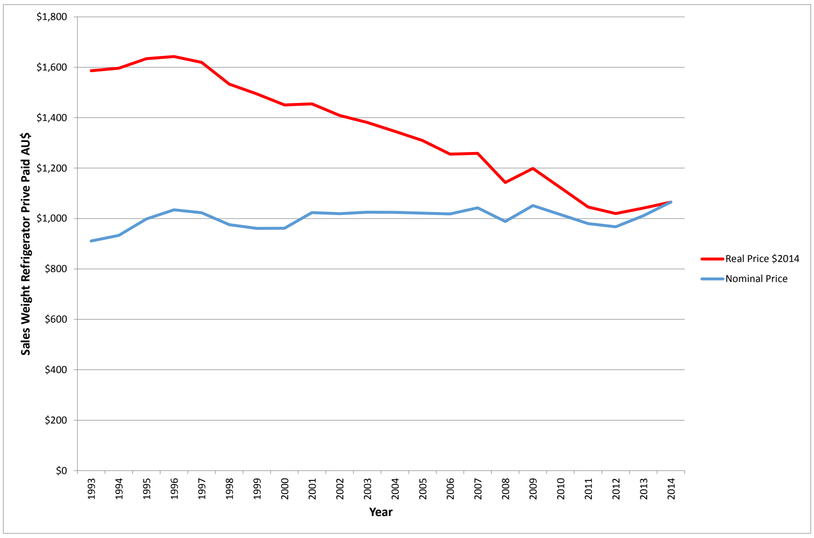

Figure 11: Changes in nominal and real prices paid for refrigerators in Australia

In Australia, the change in energy for each label class is evenly spaced across all star ratings so, as expected, the energy change per label class is not as dramatic as in Europe. Comparing energy for each label class needs to be interpreted carefully, because if there is any size bias in the formula that calculates the label class, this will show up in the average energy per class. A useful metric for examining price and energy trends is $ per litre of adjusted volume and energy per litre of adjusted volume, as shown in Table 3.

Table 3: Analysis of model data by star rating for Australia in 2013, Group 5T

Star Rating =>	1	1.5	2	2.5	3	3.5	4
Average price AU$	$954	$464	$614	$840	$921	$660	$1,588
Average volume (l)	436	223	327	431	417	322	461
Average adjusted volume (l)	518	262	383	499	489	374	528
Average Energy (kWh/year)	707	413	445	465	395	303	335
Models	4	16	73	90	10	11	2
Sales (units)	16	22'422	115'391	190'315	21794	45'326	759
Price/Adj. Vol (l)	$1.84	$1.77	$1.60	$1.68	$1.89	$1.76	$3.01
Energy/Adj. Vol (l)	1.38	1.60	1.21	0.95	0.85	0.82	0.64

Note: Group 5T is a frost free refrigerator-freezer with a top freezer with total sales of around 400,000 units per year (40% of the market). Star rating bins with few models or few sales need to be interpreted with care. The adjusted volume takes into consideration different compartment temperatures (freezer compartment volume is multiplied by a greater factor than refrigerator volume).

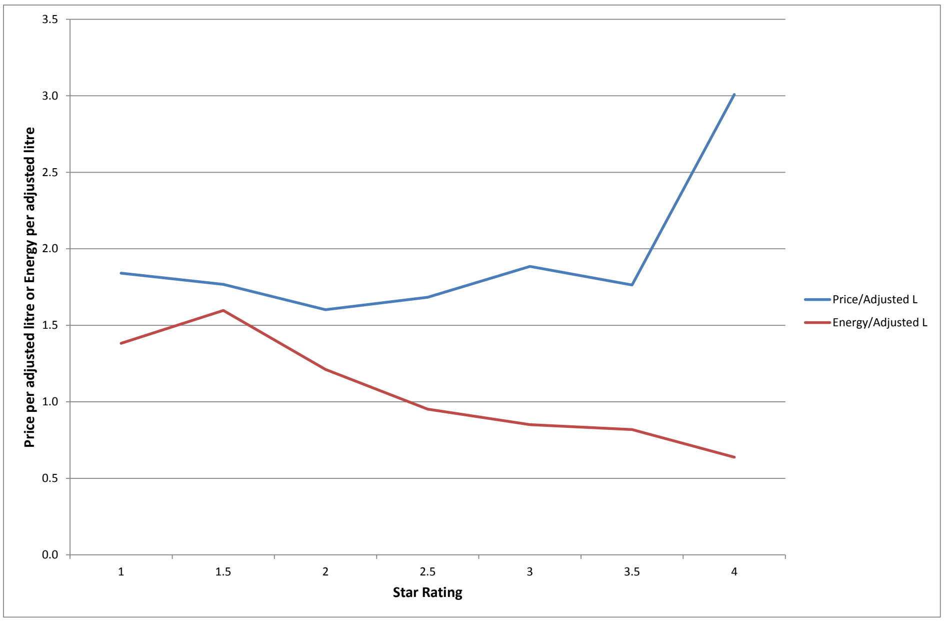

Figure 12: Analysis of price and energy per unit volume by star rating in Australia in 2013, Group 5T

The detailed analysis of individual model data shown in Table 3 and Figure 12 illustrates that the highest available efficiency class appears to attract a significant price premium for this particular product type. However, this needs to be interpreted cautiously as the price for the highest label class in this case is calculated from only 2 models (out of a total of about 300 models) with sales of less than 1,000 (out of a total of 400,000). Analysis of other refrigerator and freezer types shows that the highest available star rating on the market attracts a significant price premium for some of the types, but not for all. Analysis also shows that there is no systematic size bias in the star ratings across product categories, which is a useful finding.

Detailed market analysis of price versus energy efficiency for refrigerators on the Australian market found that, within the range of available products on the market, there was generally weak negative or often no correlation between price and energy consumption [21].

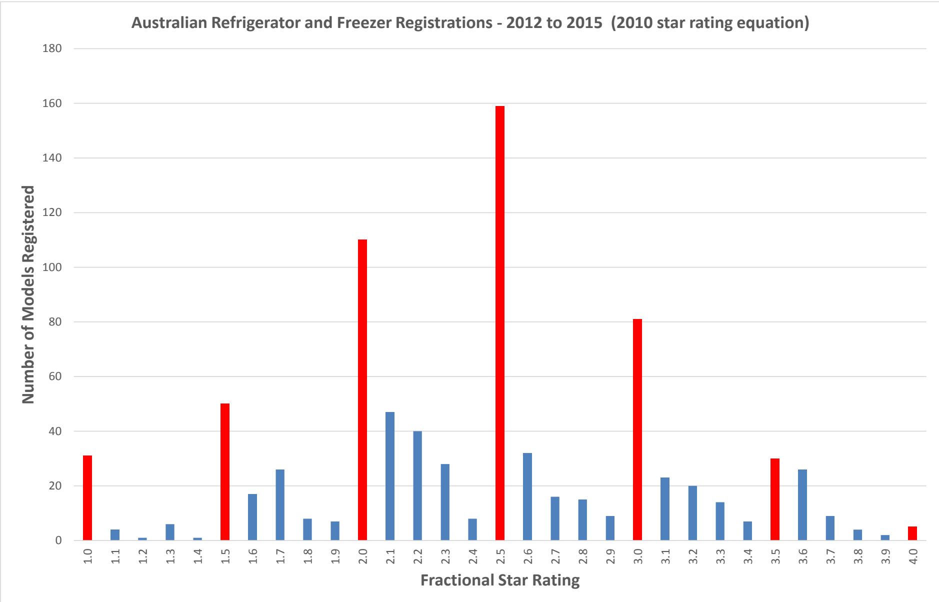

Figure 13: Distribution of star ratings for refrigerator and freezer registrations

Figure 13 shows that, while star ratings of all products registered are essentially a normal distribution, there is a much higher than expected prevalence of models with a star rating index that achieves the next highest label class within each half star bin, as shown in red. This illustrates that the label exerts a continuous upward pull on manufacturer designs with respect to energy efficiency. Suppliers have to comply with tight verification tolerances in the test standard and also supply test reports with registrations, so this effect is primarily the result of small engineering improvements in products rather than the exploitation of test tolerances. There could be small effects from selective sampling. This pattern can be explained to some extent by the fact that manufacturers do not bother to re-register their products when they make small energy improvements, except with the cumulative effect of these changes over time results in the product reaching the next half star threshold.

Can the European and Australian refrigerator markets be compared?

A comparison of analysis of refrigerator sales from Europe and Australia show many similar trends such as increasing efficiency and decreasing average energy consumption for both regions. However, there are also differences between the markets and how they respond to local policies.

Energy consumption values have to be compared with caution, but seem to be clearly higher in Australia. This is no surprise, as Australian refrigerators are larger than European models. This is likely to be function of demographic and climatic factors: a significant proportion of the Australian population do not live in dense urban areas as in Europe, but rather in sprawling suburban regions, where shops may be some distance away. Most families do larger weekly shopping rather than regular small purchases of food, so a larger storage capacity is a consequence.

Australian MEPS seem to have had a much stronger impact on the market than MEPS in Europe: their effect is clearly shown in Figure 7 and Figure 9, but this is less obvious in the equivalent EU figures. Australian 2005 MEPS were very stringent: when they were announced in 2000, there was no product on the market that would meet the level and all products had to be improved by an average of 30% within five years. After the implementation of stringent MEPS, the improvement rate from labelling slowed. In Europe, MEPS are usually implemented at low efficiency levels[6], while much of

[6] A barrier for more stringent MEPS in Europe might be the requirement that MEPS must be set at the Least Life Cycle Cost (LLCC) level, for the calculation of which constant prices are assumed. In [24] H.P. Siderius shows that prices of efficient technologies decrease over time, and proposes to use experience curves to forecast future real prices instead.

the market transformation is achieved by the ongoing pull effect of the Energy Label. As a consequence, the market improvement has occurred at a more consistent rate in Europe.

Another factor contributing to changing market responses in Australia might be the two Label re-grades, which took effect in 2000 and 2010, and visibly increased the underlying rate of efficiency improvement. European label classes have remained more or less the same, with new efficiency classes simply added on top.

Not only do the stringency and timing of policies impact the market trends, but also the definition of what is an energy efficient refrigerator – that is the mathematical formulas assigning an energy efficiency class to a refrigerator's measured energy consumption. While in Australia Label classes are evenly spaced (always 23% efficiency steps, or around 11% for half star classes), the EU Label classes require different improvements between 21% and 33% per class, which is a considerable energy reduction for a product that is already quite energy efficient. Both regions use a system of different product categories, which have different reference lines (based on adjusted volume and energy) and include a different range of products. The energy label reference line in Australia is based on the adjusted volume to the power of 0.67 ($V_{adj}^{0.67}$) to better reflect the relative changes in surface areas with size. This results in a reference line that is a curve and substantially corrects for size bias in the rating system for larger products. As straight lines are used in Europe, some size bias is inevitable. Also in contrast to Europe, in Australia there are no allowances or 'correction factors' for frost free products, chillers or any other features.

Conclusions

This paper tells a success story about household refrigerators: their energy efficiency has constantly improved over the last ten years, both in Europe and Australia. Data from Europe shows constant sales figures, a 34% efficiency improvement, a 25% reduction in average energy consumption and a very moderate price increase. Australia also shows constant sales figures with an 11% improvement in efficiency over the period 2004 to 2014 and a 19% reduction in energy. The lower levels of improvement in Australia are a reflection of the analysis period – an energy reduction of 30% was achieved from 2002 to 2014 due to new MEPS levels introduced in 2005 (much of the resulting energy savings were already achieved by 2004). Nominal product prices in Australia appear to be constant over time, with real prices falling by as much as 35% over the past 20 years. New refrigerators save energy, and consumers save money due to lower lifecycle costs in both Europe and Australia.

The data presented in this paper shows that Energy Labels and MEPS can be important drivers towards higher energy efficiency and lower energy consumption. A review of data for other product categories shows that energy efficiency can stall if efficiency improvements are not rewarded, for example, where there are no higher efficiency classes to challenge the market. To maintain market pull, Labels and MEPS need to be revised periodically, to take into account the efficiency innovations achieved by industry. Australia shows that stringent MEPS can have a big impact on the market, and that Label class re-scaling can be realized without major problems [22], although such changes do require careful planning and implementation. Defining sensible label classes necessitates some insight into how fast energy efficiency is likely to improve over time and the likely technological improvements that each industry can utilize into their future products (and their cost). This requires a good deal of judgment and expertise, as well as excellent and up-to-date data!

For monitoring the effect of past policies, making timely decisions on revisions, designing new policies at appropriate levels and quantifying energy consumption and energy savings, systematic market monitoring is invaluable. Sound data and its analysis, as presented in this paper, may come at significant cost, but can support policy makers decidedly to draw better and more effective policies, independent of industry readiness to provide own data.

With its market monitoring system, Australia can show Europe the way: the combination of GfK sales data with detailed model information from the mandatory product registration system allows tracking of highly detailed information on market changes and also supports effective market surveillance. Europe would benefit substantially from the introduction of a similar mandatory product registration system (providing detailed information about all models on the market) as well as a systematic market monitoring based on sales data from a commercial market monitoring organization for all Energy related products. The potential benefits are substantial: for example, in Australia, the energy cost consumers pay to operate all refrigerators each year is about 100,000 times more than the cost of purchasing and analyzing the market data for refrigerators each year. Undertaking this analysis is most likely a good investment. Even if such data can lead to only to a 1% improvement in energy consumption over time, the benefit cost ratio is more than 1,000 to 1. Analysis in this paper has shown that substantially larger improvements can be achieved in practice.

Recommendations for EU refrigerator and freezer policy

New A to G Label, empty top classes:

For the past two years, only label classes A+ to A+++ remain on the market. These classes are known to have limited effect on consumer purchasing decisions [e.g. 23], while the original A-G Label is clearest for consumers [8]. Australia shows that a re-grading of Label classes can increase the Label's market pull effect. The opportunity of the current EU Label revision should be used to go back to an A-G scheme, with the two top classes empty initially to account for future innovations.

Announce future MEPS:

Australia shows that stringent MEPS can have a big impact on the market. New MEPS in Europe can cut off the lower end of the market to realize the 10 TWh of potential savings per year quantified in this paper: today's class A++ should be announced as the forthcoming MEPS level in two years.

Simplify the EEI calculation formula to remove misleading features:

The EEI calculation formula must allow a direct comparison of different products by removing the current rewards for special features: one reference line (or curve) for all categories is sufficient (temperature differences are already considered in the adjusted volume) and the misleading correction factors for tropical compressors, Frost Free function, built-in models and chill compartments should be removed. The Australian reference curve has removed size bias for larger products. With the approach rationalized and revitalised, the Energy Label in Europe will do more to support the most energy-saving models, and higher efficiency will more directly translate into saved electricity.

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Why, When, and How to Utilize the "Right" Methods for Evaluation of Energy Efficiency Programs

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Abstract

Energy efficiency programs often encompass a broad range of customer segments, technologies, and delivery methods. An effective evaluation plays a critical role in the success of a program and the widespread adoption of energy efficiency. When evaluating the effectiveness of energy efficiency programs, it is useful to have an equally broad range of evaluation methods. Simply put, what works for one program type may not be feasible or optimal for another. This paper presents rationales for the use of various evaluation methods and suggests various criteria to consider when selecting evaluation methods for various energy efficiency programs.

This paper reviews several common evaluation approaches that can be categorized as engineering analysis, simulation modeling, and econometric/survey analysis. The paper provides a discussion of typical program characteristics that may present suitable opportunities to apply specific evaluation methods. While optimal evaluation methods will generally differ based on specific circumstances, this paper includes some ways in which evaluators may select the "right" methods to evaluate energy efficiency programs—balancing cost, timeliness and accuracy to achieve optimal results. The paper concludes with examples of evaluation methods selected from a sample of the authors' recent engagements, discussing these various evaluation techniques in the context of how, and why, each was used to assess impacts from a variety of program types.

Introduction

Energy efficiency (EE) programs often encompass a broad range of customer segments, technologies, and delivery methods. [1] An effective evaluation plays a critical role in the success of an EE program and the widespread adoption of energy efficiency. Evaluators must weigh several factors when selecting an appropriate evaluation methodology for a given EE program. Three factors that frequently have the greatest impact on selecting appropriate program evaluation methods are cost, timeliness, and accuracy. [2, 3, 4, 5] Like any other effective project manager, evaluators are beholden to the given budget and schedule for a program's evaluation. These constraints provide a constant counter-balance to the need for accuracy in a program's evaluation findings. Of course, evaluators that would like to maximize the accuracy of an evaluation must also keep in mind the evaluation timeline and project budgets.

Conversely, many program evaluations must meet a minimum threshold of accuracy to satisfy regulatory requirements of a public utilities commission (PUC) or regional transmission organization (RTO). The role of the evaluator, therefore, is to create a fine balance between delivering accurate results on the one hand and meeting reporting budgets and timelines on the other. The evaluator achieves this balance by selecting the "right" evaluation method. This paper discusses various program evaluation methods and outlines a selection process for consideration when seeking to find the balance between cost, timeliness and accuracy to achieve effective results.

Program Considerations and their Influence on Evaluation Needs

An evaluation method that works for one program may not be the most appropriate method for another program. For example, evaluating a small business lighting program[1] may only require a low level of rigor, such as an evaluator reviewing project documentation and purchase invoices to verify that the equipment was installed and is operating as planned. Since these projects are small in scope and the

[1] A small business program typically targets first tier business consumers within a service territory. It is also common for small business programs to be direct install programs that partner with local contractors. Small business programs usually offer measures to target energy, gas, or water savings or any combination thereof.

parameters[2] for calculating savings are relatively certain, these projects may be evaluated using a relatively simple engineering approach. However, in a custom program,[3] one with projects that are unique by definition, projects are often large and may have high uncertainty around savings. Evaluators of these programs will likely determine that these projects require a moderate- to high- level of rigor. Evaluation activities for these projects may include conducting a site visit and using metering devices to calculate with certainty the savings achieved.

In yet another situation, choosing engineering approaches to conduct an evaluation may not work at all. Take, for example, a program that influences behavioral changes; this could be something as simple as including energy saving tips in home energy bills.[4] To evaluate savings in this case it may be most appropriate to perform an econometric billing analysis. This type of evaluation includes comparing pre- and post- billing data for participants as well as non-participants to identify savings that may be attributed to the program.

It is helpful to visualize the tradeoffs between these three factors – cost, timeliness and accuracy – in a triangular configuration, as demonstrated in Figure 1 below. This balancing act is further discussed in the Selection Methodology section.

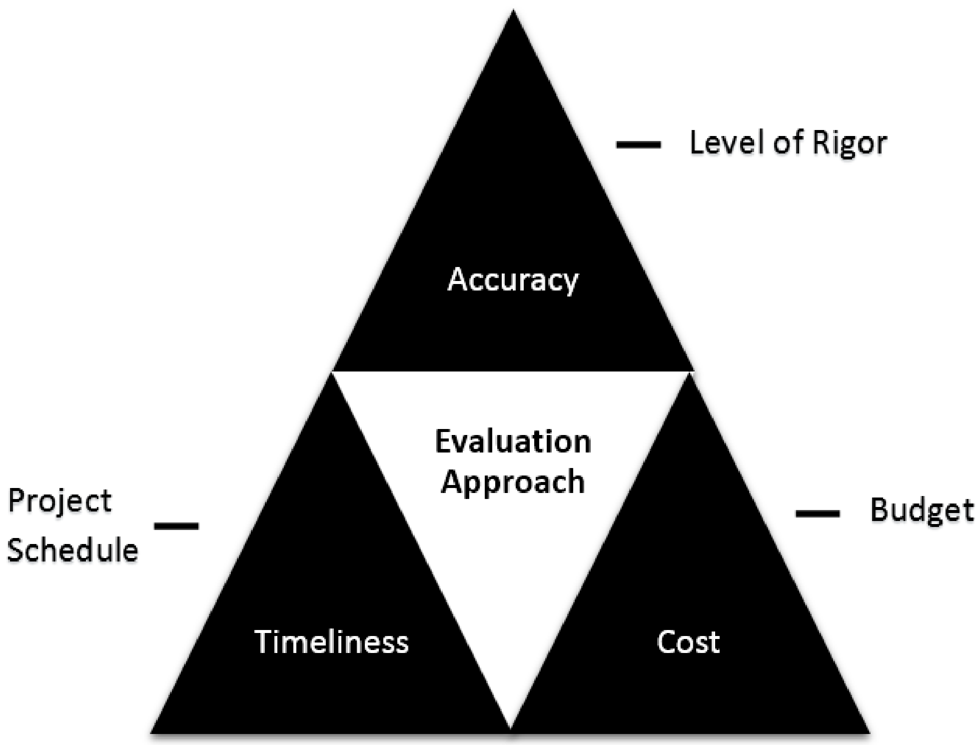

Figure 1. Balancing Act: Cost, Timeliness and Accuracy

Source: Authors

Evaluation Methods – The Evaluator's Toolbox

For any evaluation, an evaluator has a number of methods that he or she must select from in order to provide accurate results within the given budget and schedule. Before a fruitful discussion of evaluation method selection criteria can occur, we must first reach a common understanding of frequently used methods at the evaluator's disposal. The methods described in this paper are those which can be used

[2] Measure parameters are used to calculate savings, e.g. hours of operation is a lighting measure parameter.
[3] Custom programs can apply to any market sector, but most typically will be offered within the commercial and agricultural sectors. Custom programs incentivize large, complicated, or unique projects that do not easily fall into a prescriptive program with deemed savings.
[4] Behavioral programs are designed to provide information or education about energy consumption and efficiency to customers in order to incite behavioral changes to achieve savings.

to quantify the impact of energy efficiency programs.[5] The goal of impact evaluations is to measure and verify the quantity of energy savings achieved by the program over a given time period. [6] Program impacts are frequently quantified according to kWh (electricity savings), kW (demand reduction) or therms (natural gas savings), but may also be reported in British Thermal Units (BTU) or other metrics. Figure 2 shows common evaluation methods grouped into three overarching categories: engineering, modeling and econometric. These are approach based categories, engineering methods typically focus on specific measures or parameters, modeling methods center on complex or interactive systems, and econometric methods are a statistical approach to quantifying savings. Additionally, the methods under one category do not have to be used in isolation, but in fact are often used in combination with or to reinforce evaluation methods in the same or other categories. Each of these categories requires personnel with unique skill sets, specialized equipment or software and advanced knowledge in order to be used effectively for evaluation purposes. Each category and methodology [7, 8] is described briefly below.

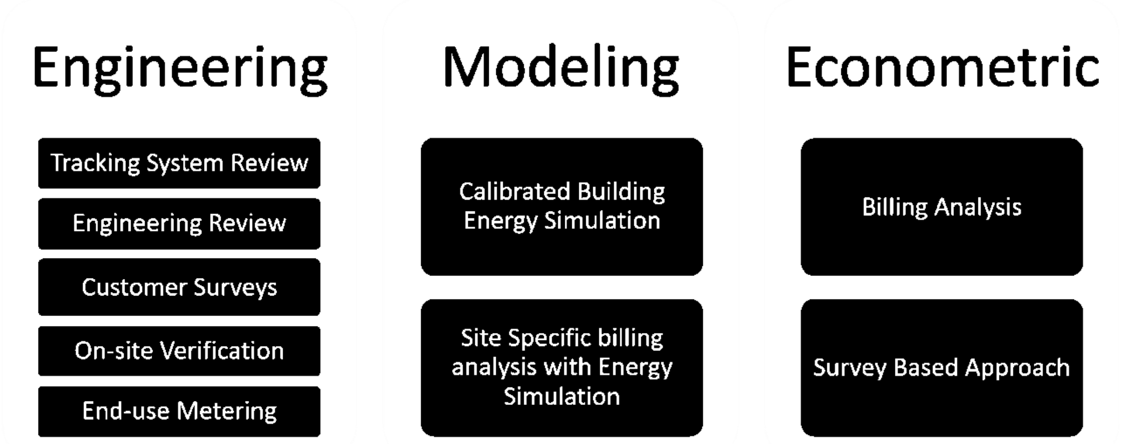

Figure 2. Evaluation Methods

Source: Authors

Engineering Methods

Engineering methods used for energy efficiency evaluations seek to isolate and quantify savings of specific measures or a group of measures using engineering analysis. Typically, input parameters are gathered via literature review, project documentation or onsite measurements. These parameters are used in engineering algorithms to quantify energy savings.

- **Tracking System Review** is an important early step of the evaluation effort. A program tracking system is generally managed by the program implementer and includes detailed information about the participating customers, specific measures, program cost, program services etc. The purpose of the tracking system review is to ensure that these systems gather the data required to support the program evaluations and to monitor key aspects of the program performance at regular intervals.
- **Engineering Review** involves examining engineering assumption and estimates used to derive measure savings in order to verify and/or update assumptions used in the engineering-based formulas or algorithms. Some measure savings may be “deemed” for inclusion in a Technical Reference Manual or other reference document while others may be contained in project documentation, such as a measure work paper. The results of an engineering review may result in refinements to the current algorithm, the inputs to the algorithm, or an entirely new engineering model.
- **Participant Surveys** offer an approach to verify energy savings by contacting program participants. Participants are asked specifically about measures reported in the program

[5] There are four common types of energy efficiency program evaluations: process evaluations, impact evaluations, cost-benefit evaluations and market assessment evaluations. This paper focuses on methods used for impact evaluations of energy efficiency programs.

database for which they were involved. Surveys can provide sufficient information regarding measure installation rates, equipment specifications, operating conditions and participant's motivations. Surveys can be conducted in the form of telephone or web/online surveys.

- **On-site Verification** may encompass a range of activities, including verification of measure installations, measure counts, capacities, and efficiencies, equipment specification checks, operational observations, discussions with building operators about building construction features, occupancy schedule, energy systems characteristics, and confirmation of baseline conditions (as possible).
- **End-use Metering** may involve on-site performance measurement and metering activities such as spot measurements (one-time measures of technology, system or environment), run-time hour or time of use data logging (recorded profiles over given time period) and interval metering (real-time monitor of energy use over given time period).

Modeling Methods

Model based methods are used when it is impossible or infeasible to calculate savings using engineering algorithms. These methods often leverage computer programs that allow for solving of more complex and interactive systems. These models may be used to determine savings for one specific project or to determine savings, in general, for measures in different building or sector types.

- **Calibrated Building Energy Simulation Modeling** involves using engineering-based models or building energy simulation software to calculate energy flows and consumption to verify savings. It can leverage tracking data, customer project files and secondary data to combine building characteristic data and weather data to more accurately estimate savings.
- **Site Specific Building Energy Simulation Modeling** again involves engineering models or simulation software to determine baseline and efficient consumption for a specific site. Evaluators can use primary or secondary site-specific data as inputs or to calibrate the model to verify savings.

Econometric Methods

Econometric based methods make use of data and statistics to compare energy consumption of groups implementing energy efficiency when it is difficult to disaggregate energy savings. These methods may make use of billing data or customer surveys to inform quantified savings of a participant group.

- **Billing Analysis** involves analysis of the utility meter (or sub-meter) data using techniques from single comparison to multivariate regression analysis. Billing analyses can be sensitive to sample sizes and the relative sizes of the savings as compared to the total customer consumption. Econometric analysis of the historic billing data, often at the interval level, is done for the large and complex programs. Additionally, econometric methods can be used to compare the results of the participants and non-participants groups. Such analysis provides the net energy benefits attributable to the program.
- **Survey Based Approach** involves collecting information about the program that can be expressed in terms of statistics. This approach is similar to the customer surveys discussed under engineering methods. However, in this case, the collected information is further analyzed using econometric methods to characterize the program's progress, assess customer satisfaction, and answer stakeholder questions, etc. Survey data may also be analyzed to show relationships, compare groups and determine trends over time. The key challenge in the econometric survey based approach is to appropriately reflect target population and avoid any biases in the results. Therefore, it is important to design a survey sample such that it meets required confidence and precision within given time and budget constraints.

Selecting the Most Appropriate Evaluation Method

There are many factors to consider when matching an evaluation method to a program. There is no "right" answer to finding the optimal balance between objective and formative evaluation activities that applies to every case equally. In a world of finite resources, each evaluation must balance cost, timeliness and accuracy, based on evaluation priorities as identified through client preferences, regulatory requirements or other sources.

On one side of the balancing act is the requirement or preference for a certain degree of accuracy.[6] Not all measures or programs are evaluated with the same level of rigor for a variety of reasons that are briefly described below. Two other factors create counter-balances to selecting a level of rigor or accuracy for evaluations -- timeliness[7] and cost.[8] [9] While frequently intertwined and closely related, timeliness and cost are not always found hand in hand. For example, an evaluation with a high degree of rigor and cost, such as end-use metering, may be produced in a relatively short amount of time. Conversely, an evaluation using metered results may produce results using a high-level of rigor over a long period of time, but be relatively inexpensive to conduct. Table 1 presents typical evaluation methodologies that an evaluator may use and their associated level of cost, timeliness and accuracy.

Table 1. Evaluation Method Selection Guidelines

Evaluation Method	Accurate	Timely	Cost - Effective
Tracking System Review	○	●	●
Engineering Review	◐	●	◐
Customer Surveys	◐	◐	◐
On-Site Verification	◐	◐	◐
End-Use Metering	●	○	○
Calibrated Building Energy Simulation Modeling	●	◐	◐
Site Specific Energy Simulation Modeling	●	◐	○
Billing Analysis	◐	●	◐
Survey Based Approach	◐	◐	○

Source: Authors

Once the evaluator is familiar with the common impact evaluation methods described above, the evaluator now faces the difficult task of selecting the appropriate methodology for the program evaluation considering the need to balance level of rigor, schedule and budget for the assignment. A frequent best practice for beginning an impact evaluation is assessing the relative contribution of each program or measure to the energy efficiency portfolio[9] or program savings, assessing the uncertainty around each program's measures,[10] and reviewing the percent of annual portfolio or program budget allocated to each program.

Results of the initial assessment will enable an evaluator to prioritize (i.e., apply a higher level of rigor to) those programs with measures that have a large contribution to portfolio savings, have high cost per first year of savings, and/or have a high degree of uncertainty around those savings. Frequently,

[6] Accuracy is achieved in part by applying the appropriate level of rigor to an evaluation analysis.
[7] Timeliness is the amount of time required to perform the evaluation tasks and report results.
[8] Cost is the amount of money required to perform the evaluation tasks and report results.
[9] An energy efficiency portfolio consists of the suite of programs offered through a utility.
[10] A program measure is the technology, equipment, or service provided through the program, e.g. compact fluorescent light bulbs.

measures or programs that score high on one or more aspects of the initial assessment described above should be prioritized by the evaluator because the impact evaluation will reduce uncertainty and risk associated with those program elements. Evaluators should also review existing regulatory requirements and consider recent updates to codes and standards that may affect program or measure savings. Other criteria that would factor into the evaluation methodology are the priorities of the PUC/RTO and the client. Figure 3 below provides a list of factors for evaluators to consider when selecting evaluation priorities.

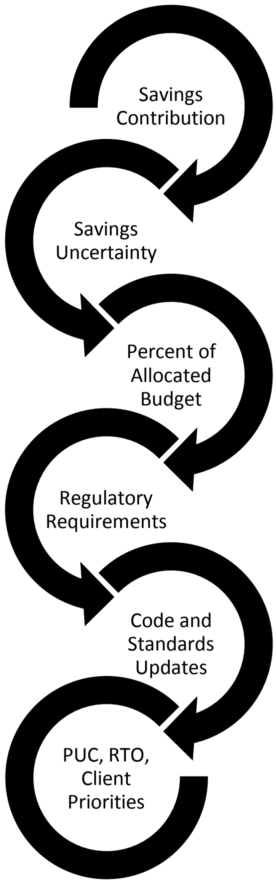

Figure 3. Considerations for Selecting Evaluation Priorities

Source: Authors

There are always constraints that exist and an evaluator needs to balance these constraints. The most rigorous and accurate method may not always be the most practical. When approaching evaluations with multiple objectives, it is helpful to have a systematic context in which to make decisions about the selection of evaluation methods. To this end, the evaluator may choose follow two widely used industry protocols, the International Performance Verification and Measurement Protocol (IPMVP) [10] and the Uniform Methods Project (UMP) [11] to help guide evaluation method selection.

Real World Examples of Selecting Evaluation Methods

The methodology an evaluator chooses depends on the characteristics of the program, measure, or parameter that is being evaluated. Does the measure or parameter already have significant research that will help quantify savings? Does the program have many unique and complex projects? Are the savings directly measurable or are they more behavioral in nature? These are all questions an evaluator may ask when selecting a methodology. Table 2 below includes a list of program categories and measures and corresponding evaluation methods for each. Examples used in this table are for illustrative purposes only. Real world examples from the authors follow the table and help to illustrate the evaluation trade-offs required in specific circumstances.

Table 2. Examples of Typical Evaluation Methods by Program

Sector	Program Category	Program Measures	Typical Evaluation Method
Residential	Whole Home Programs	Whole Home Retrofit, Home Performance, Weatherization	Engineering review, customer surveys, on-site verification
		Audits – standalone, onsite	
	Consumer Products Rebate	Lighting, HVAC	Engineering review, customer surveys, on-site verification, end-use metering
		Appliances and Appliance Recycling	
		Electronics	
Residential/ Commercial	Upstream Incentive	Lighting	Engineering review, customer and distribution surveys
		HVAC	
	Customer Rebate	New Construction	Engineering review, customer surveys, on-site verification, end-use metering
		Direct Install	
	Behavioral Programs	Outreach/ Education	Billing analysis, survey based approach
		Rewards	
		Benchmarking	
	Demand Response	Time of Use Pricing	Energy simulation modelling, end-use metering
		Real-Time Pricing	
		Critical Peak Pricing	
		Peak Time Rebate	
Commercial	Custom	Whole Buildings	Calibrated building simulation analysis
		Retro-Commissioning	Site specific energy simulation modeling
		Energy Management Systems, Controls	Site specific energy simulation modelling, billing analysis
		Compressed Air, Data Center IT	Site specific energy simulation modeling
	Prescriptive	HVAC	Engineering review, customer surveys, on-site verification, end-use metering, calibrated building simulation modeling
		Refrigeration	
		VFDs	
		Lighting	
Agricultural	Custom	Greenhouses, Irrigation	Engineering review, customer surveys, on-site verification, billing analysis

Source: Authors

As shown in Table 2, often more than one methodology can provide acceptable results for a given program type. An evaluator must carefully consider **cost, timeframe, and accuracy constraints** when selecting which methodology will provide the "best" results for a given program. For instance, consider the following evaluation methods selected by the authors in recent engagements:

- **Example 1 – Evaluating New Programs within Budget Constraints**. A client has just started to implement EE programs in a new territory. They have a portfolio that includes commercial prescriptive HVAC, refrigeration, lighting and VFDs. Since the portfolio is new and relatively small the client would like to know the distribution of energy savings, but they are on a tight budget. Looking at Table 2, it is clear that an evaluator has a number of methods that could be used to evaluate this portfolio. In this case, due to budgetary constraints, the authors chose an engineering review and a tracking system review as the most appropriate methods. These methods will provide the necessary level of accuracy to meet reporting requirements, the methods will enable the client to achieve their goal of increasing energy savings through their current program offerings, and are implemented within the client's budget for evaluation activities.

- **Example 2 – Expedited Evaluation Schedule for Future Program Planning**. A client is looking at evaluating participant savings in an upstream lighting program. The client would like to determine whether or not they should continue the program for the next year and is looking for results quickly to fit them into the planning process for the next year. In this case, the authors chose to implement an in-store intercept survey. This method enabled the client to determine participant savings in a short period of time. Other evaluation methods for this type of program, although applicable, would be costly and time consuming for the client in this example.

- **Example 3 – Market Requirements Dictate High Level of Rigor**. A client is looking to "bid" energy savings into a forward capacity market from their commercial and industrial custom program. The regulatory requirements are such that a high level of accuracy and rigor is required for these savings to be considered eligible to be bid. In addition to the regulatory requirements, custom programs have high-levels of uncertainty and data accuracy is paramount. Since the client will be able to recover costs from the energy efficiency program in the forward capacity market they are able to afford additional costs to get accurate results. For this scenario, end-use metering would be most appropriate since it provides highly accurate results and budget concerns are minimal.

Conclusion

The diversity of energy efficiency programs in operation today is reflected in the corresponding variety of evaluation methods available to quantify program impacts. An effective evaluation plays a critical role in the success of a program and the widespread adoption of energy efficiency. The optimal role of the evaluator is to balance accuracy priorities with budget and schedule constraints of the evaluation to determine the most appropriate or "right" evaluation method for a given assignment.

The evaluator can choose from various approaches from three categories of impact evaluation techniques—engineering, modeling, and econometric. Each has a number of methods available for the evaluator to attempt to maximize the accuracy of the evaluation while keeping the study on time and within budget. This balancing act can be aided with the evaluation methodology selection guidelines outlined in this paper and from industry standard sources. The selection guidelines describe reasonable steps to prioritize programs, measures, or parameters that stand to benefit most from an impact evaluation.

As Europe and much of the world increase investment in energy efficiency to meet climate goals and achieve specific national priorities, policy makers must ensure that the programs receive evaluation of sufficient rigor to ensure that the investments are justified. Selecting the most appropriate evaluation methods can cost-effectively provide sufficiently accurate results in the timeframes required by policy makers.

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Major role of households specific electricity in total energy consumption of apartment buildings

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Enertech

Abstract

Whereas household heating consumption is ineluctably decreasing in EU zone, specific electricity consumption in residential sector is fluctuating and has not decreased despite EU regulation policies over the last two decades. As already observed and assessed in recent French energy efficient buildings, representative laboratory of tomorrow residential situation, domestic electricity will soon become the major issue to handle. Monitoring campaigns showed specific electricity could represent up to 90% of total household consumption in recently monitored passive social housing building. This soon coming trend will lead to multiple social, economical and technical consequences not anticipated today.

Monitoring campaigns since 20 years showed that domestic electricity consumption structure drastically changed and is in constant and rapid evolution. Unitary consumptions of several equipments decreased, mainly thanks to EU directives. But these energy savings have been compensated by increase of ownership level, appliances size, as well as emergence of new devices as ICT and audiovisual equipments.

Except from the REMODECE project, very few monitoring campaigns of household electricity consumption have been conducted so far at the European level. In France, monitoring programs are regularly carried out since 1996 but in insufficient amount to allow a comprehensive and dynamic follow-up of household electricity consumption trends. Ongoing performance monitoring is necessary to understand how energy consumption changes and subsequently to tailor and to evaluate action.

Reducing energy consumption means evidently acting simultaneously on technologies and behaviours. Long-term relevant assessments are also missing and absolutely necessary for numerous awareness raising actions implemented nowadays.

Introduction

During the last ten years, numerous programs have been implemented in order to reduce buildings energy consumption, focusing mainly on heating consumption, because of its dominant energy load. Even if goals are not always strictly achieved, their positive impacts have been assessed by monitoring campaigns (see Renaissance and SESAC projects in Concerto Program). They show that thermal performance is overall under control in new or refurbished buildings.

Inside EU zone, households heating consumption has decreased almost everywhere; with more than 25% reduction in average between 2000 and 2012 (figure 1). This decreasing trend is an ongoing process and is expected to continue in the future.

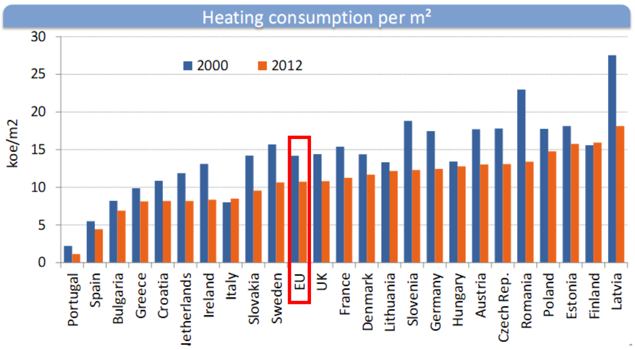


Figure 1: Evolution of households' heating consumption. [1]

On the other hand households' specific electricity consumption has followed an opposite trend with a slight increase since 2000 in most EU countries (figure 2) despite proactive EU framework directives.

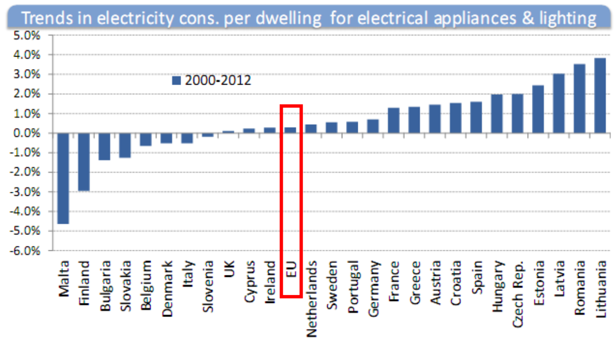


Figure 2: Evolution of households' specific electricity consumption. [1]

Households' specific electricity consumption plays therefore automatically an increasingly important role.

Thanks to monitoring campaigns in a large number of energy efficient buildings (new or refurbished), which prefigure the residential sector of tomorrow, we can observe and anticipate what will happen in coming years for the whole housing stock. As we will see below, *households specific electricity will soon become the major issue to handle regarding to residential energy consumption* (the same trend is observed for tertiary sector).

As illustration, recent monitoring of a French passive social housing building showed that households' domestic electricity consumption is twice that of all remaining uses (heating, hot water, ventilation) in primary energy.

Remark: embodied energy will also become a huge stake for building sector, but we chose to focus here on operating energy only (reliable data are deeply missing concerning embodied energy in buildings and households equipment).

We will present and analyse thereafter the results of large monitoring campaigns since 20 years in hundreds of households. On the light of these precious field feedbacks, we will open the discussion on possible levels of action and draw opportunities to move further on energy savings in residential sector.

Method

The main originality of the present paper is to rely on large and exhaustive monitoring campaigns of real energy consumptions in housing buildings, which constitute a very powerful and precious "raw material".

[1] Source: Energy Efficiency Trends for households in the EU ; Lessons from the Odyssee-Mure Project ; 2013

Since 20 years, Enertech has completed among the largest metering campaigns in the world, in France and abroad. The measurements are done with a record interval from one second to one hour.

The presented results are strictly actual consumptions and exact observations of annual households' energy use. The rate of non-followed uses is generally below 5% and absolutely no algorithm or calculations hypothesis are taken.

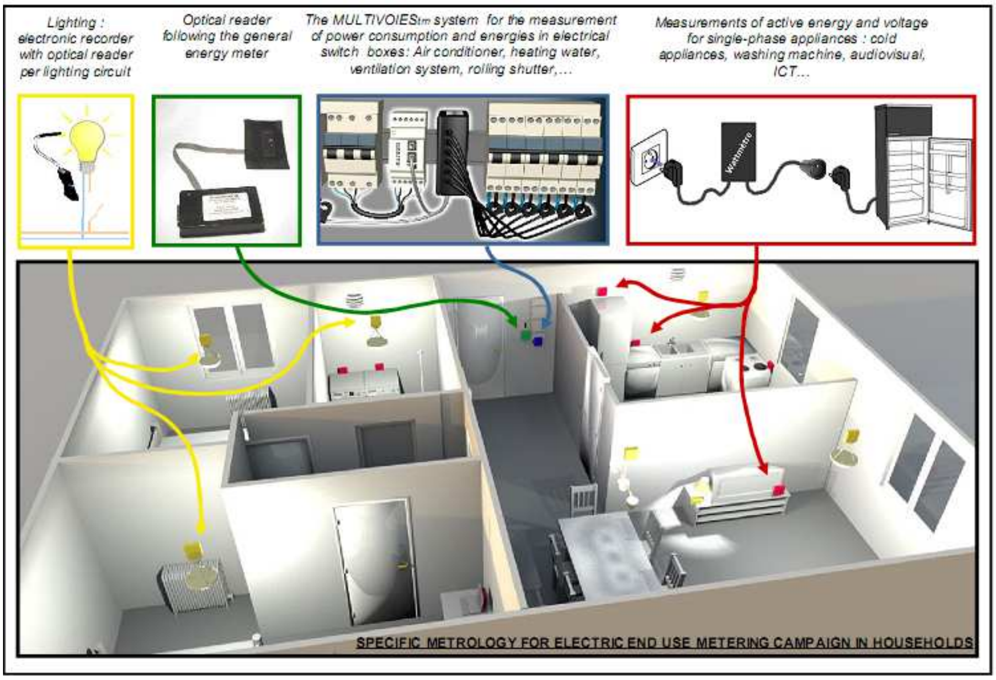


Figure 3: Description of the metrology used for households monitoring campaigns

Statistical representativeness of monitoring samples

A crucial aspect for monitoring campaigns is to assess at which extent the results on a specific sample are representative of the whole housing stock and what the statistical error margins related to sample size are. Statistical specific studies [1] show that:

- The order of magnitude of the uncertainty committed when estimating values on the entire French park with a sample of 100 units is 10%.
- The uncertainty is proportional to the standard deviation of the study values.
- The uncertainty is inversely proportional to the square root of the sample size: in order to divide the uncertainty by factor 2, the size of the sample should be multiplied by factor 4.

Concerning Enertech monitoring campaigns in France, the error margin appears to be below 10%. Observations and findings are thus to be considered as very reliable.

Such large and comprehensive studies on actual energy consumptions are extremely rare. As illustration of exceptional added value and reliability of processed monitoring campaigns, Enertech were asked to provide raw material data (unitary equipment consumption, daily load curve, etc) to many major institutions as European commission (EuP directives preparatory works), ERDF and RTE (French manager of the electricity network) or NegaWatt energy transition 2011 scenario (www.negawatt.org) which is still today the most elaborate and detailed prospective document on energy use in France.

Results

Increase of households' specific electricity importance

As described in introduction, due in particular to regular strengthening of thermal regulations of Member States, heating consumption is ineluctably decreasing in the whole EU zone.

It will even appear in a near future as a marginal amount of the energy balance for new buildings, as the recast of directive 2010/31/EU on the energy performance of buildings sets a target for 2020 of nearly zero-energy for new buildings.

As illustration figure 4 represents evolution of French residential building heating consumption over the last 40 years: a 2015 standard building (thermal regulations compliant) uses for heating 5.4 times less energy than an average building in 1975.

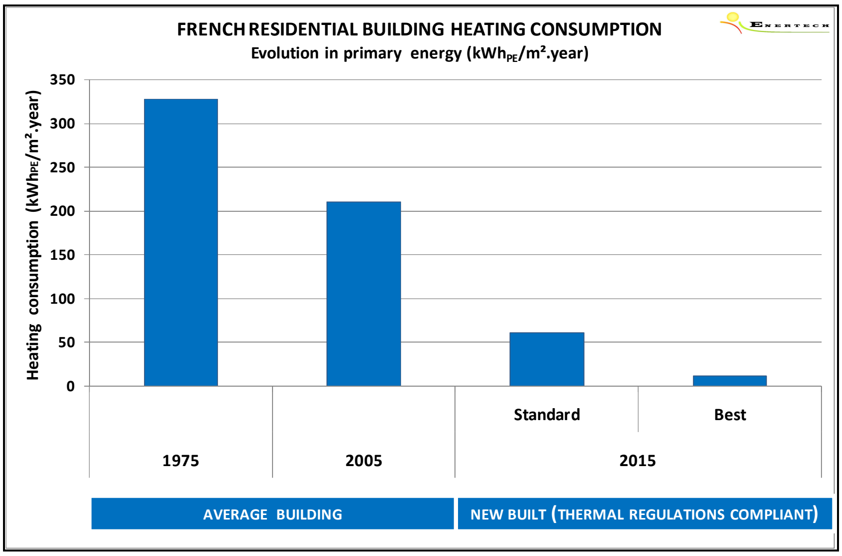


Figure 4: Evolution of French residential new building heating consumption over the last 40 years

Existing buildings will evidently durably remain the main issue to handle (for example in France new buildings represent annually only 1% of the whole park) but case studies on energy efficient building refurbishment lead to very close observations as for new construction. The main issues for renovation are actually neither a technical nor an economical problem, but a political and organizational process to set up (refer to [2] and [3] for more development) and the acquisition of the required know-how by the whole building professionals.

Due to decrease of heating consumption, household specific electricity will become a growing issue. This is already the case on energy efficient buildings. The following results are focusing on recent energy efficient buildings (new construction or refurbishment) mostly in the French context but also in some other European countries. As previously assessed, this field of study represents an exceptional laboratory to anticipate coming evolution on the whole European housing stock. The drawn observations and conclusions have to be considered as a particularly relevant forecast for the near future European residential sector.

Figure 5 presents the energy distribution of 12 French energy efficient buildings that have been constructed or renovated during the last 7 years (results of one year on site monitoring campaigns). Household specific electricity represents between 29 and 65% of the total building consumption in primary energy, which is to say 0.6 to 10 times more than heating consumption. In a logical way, the less energy is used in a building for heating purposes, the bigger the weight of specific electricity is (see extreme example of *Ancone* on figure 5).

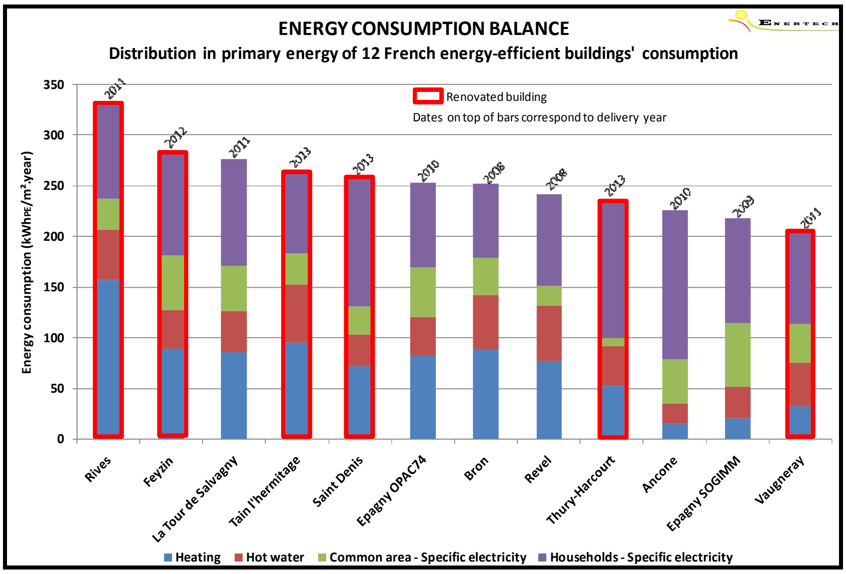


Figure 5: Energy distribution between heating, hot water, general services and household specific electricity (results of on-site monitoring campaigns) [4]

Multiple consequences of this coming major role played by domestic electricity have to be extremely seriously considered:

- Producing electricity is never neutral for environment (greenhouse gas emissions, radioactive waste generation, etc)
- In well insulated buildings, domestic electricity becomes the principal responsible for overheating; summer comfort is a sensible issue in very efficient buildings and can not be reached with high level of electricity consumption. Figure 6 shows the distribution of internal heat gains monitored during summer 2003 in an intermediate energy efficient residential building (heating consumption of 65kWh/m².year). *Household equipment represents half of the total internal heat gains.* It increases the room temperature by 2°C.

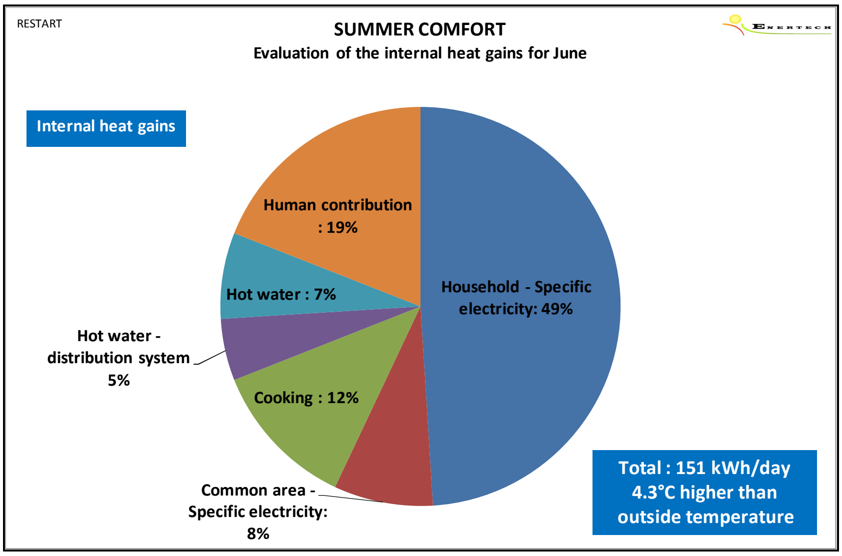


Figure 6: Summer comfort – Distribution of internal heat gains monitored during summer in an intermediate energy efficient building [5]

- Given the overwhelming importance of electricity weight in tomorrow households (up to 90% of total consumption in existing passive buildings as shown in previous chart), efforts repartition to reach performance have quickly to be moved on from thermal aspects (overall under control) to specific electricity.

- Specific electricity consumption becomes also the major contributor to energy bills in efficient buildings. Electricity is three times more expensive than heating in nowadays French new buildings, and five times more in nearly-zero energy buildings.

Evolution of household's electricity consumption structure

On several monitoring campaigns, electricity consumption has been broken down into different uses. Figure 7 gives examples of disaggregation for France in 1996 [6] and England in 2010 [7].

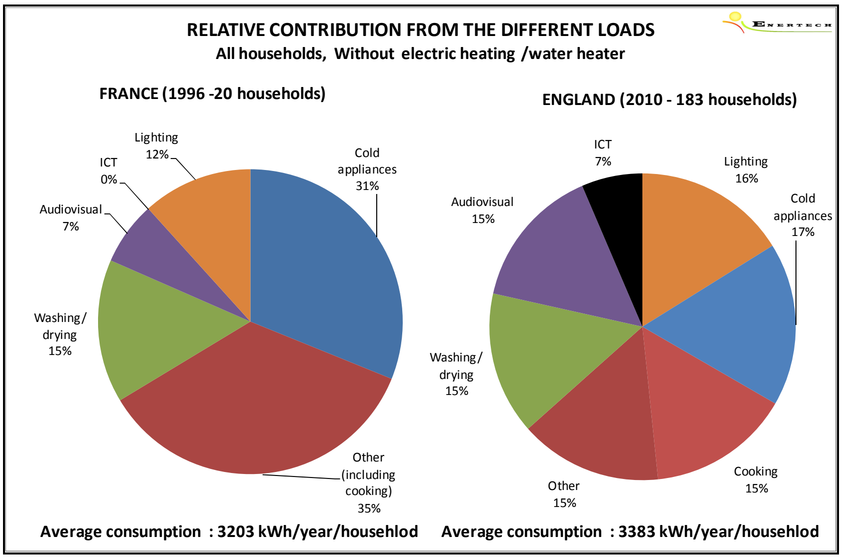


Figure 7: Distribution of household electricity consumption for France-1996 and England-2010

Energy distribution has completely changed over the last 20 years because of:

- The decrease of electricity unit consumption of equipment (progressive phase-out of less efficient appliances, energy label effect).
- The increase of the level of ownership, size of appliances performances (cold, washing, televisions…) and use rate (on/off time of lighting, computers…).
- The emergence of new devices in particular in ICT and audiovisual sectors. ICT constitutes 8.5% of French household consumption in 2012 whereas there was no computer in households monitored in 1996.

Except from the REMODECE project [8], very few monitoring campaigns of household electricity consumption have been conducted so far at the European level. In France, monitoring programs are regularly carried out since 1996 but *in insufficient amount to allow a comprehensive follow-up of household electricity consumption evolution*.

Lessons learnt at French level from monitoring campaigns on the different uses

Analysis of large sample of equipment consumption evolution since 20 years is particularly rich in teachings. In this paragraph we examine the evolution of technical features and electricity consumption for the main equipments. Given the limited size of the sample (mostly less than 100 appliances a year) trends have to be considered rather than unitary consumption absolute values.

Cold Appliance

Significant progress on energy efficiency has been made for major household appliances between 2008 and 2012 by placing on the market new models consuming 30 to 60% less. Since then improvement of performance seems to slow down. Standard models sold today are as efficient as the best appliances sold five years ago (selected by Top Ten [9]).

Unfortunately, real concrete impacts of the European regulation policies, depending on existing household stock, has still not been assessed. Figure 8 illustrates the benefits of evaluating the actual consequences of a directive. The graph presents consumption of 259 French fridge freezers monitored on-site over the last twenty years. After 14 years of linear decrease (1995-2009), the consumption seems to stabilize. In a logical way, effects of updated energy label (2011) and phasing out of the worst-performing products (2010: class B, C D, 2012: class A) – are still not noticeable.

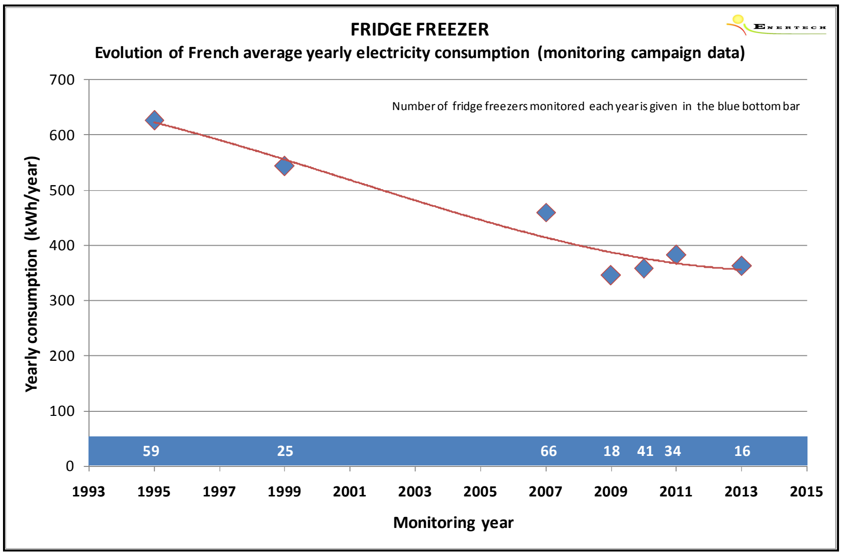


Figure 8: Evolution of electricity consumption of French fridge freezer over the last twenty years

Figure 9 compares, for fridge freezers, french monitored and forecasted consumptions – average consumption of the stock of fridges for a given year- (preparatory study for EuP directive [10]). The current trend is different from expectations and questions, at least for this appliance, on the adequacy of the directives (derived from hypothesis of preparatory study) for « 20-20-20 » target.

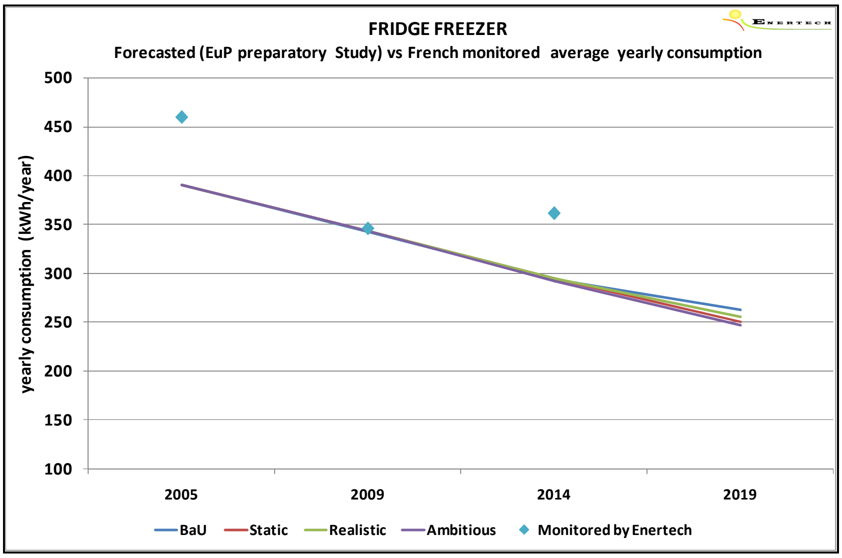
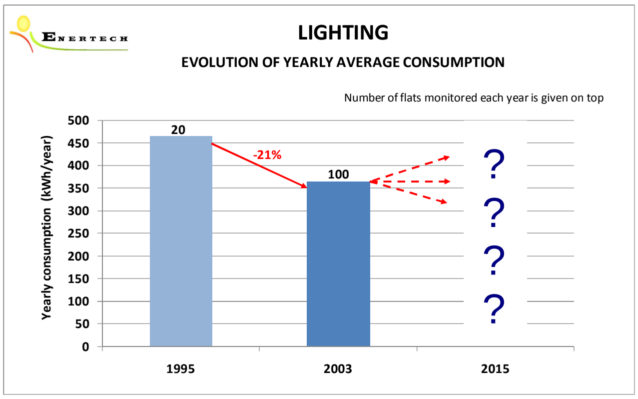
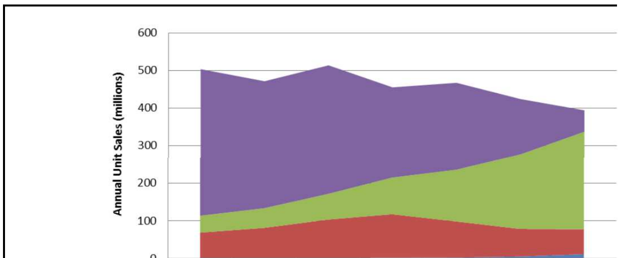


Figure 9: Comparison between actual monitored and forecasted (EuP preparatory study) consumptions for fridge freezers

Lighting

For lighting, electricity actual savings are probably even further away from forecasted potential of EuP preparatory studies. Indeed some collateral effects of directives have not been anticipated. This was the case for the ban of incandescent light bulbs. The sales data (see figure 10, right) indicates that regulation has failed to switch incandescent toward sales of CFLs (400% more efficient than incandescent lamps), and instead has simply switched to halogen lamps (only 20% more efficient). The sales market in 2013 contrasts sharply with the forecasts prepared in 2009: it was expected CFL sales to be 4 times larger than mains voltage halogen lamps in 2013 [11]. In 2013, the actual CFL sales are only one quarter of halogen sales.





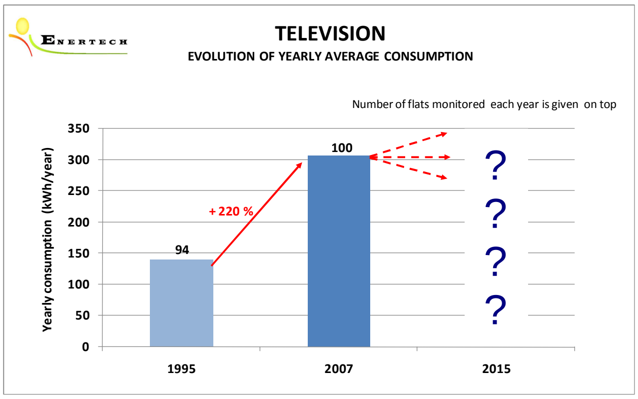
	2007	2008	2009	2010	2011	2012	2013
MV Incandescents	389.9	337.9	342.1	240.1	231.3	147.4	57.0
MV Halogens (single-end)	44.9	52.2	68.2	97.3	137.4	198.0	259.4
MV Self-Ballasted CFLs	68.5	80.8	102.3	116.0	96.0	73.6	66.6
Retrofit LED Lamps	0.2	0.5	1.1	1.7	2.5	5.0	11.0

Figure 10: Evolution of monitored electricity consumption and sales (by technology) of lamps [12]

Television

Between 1995 and 2007 televisions consumption has more than doubled due to market and habits evolution. In the last decade several major changes had an impact on electricity consumption:

- Fundamental change of supply (Led television) (figure 11)
- Reduction of price of large television
- Introduction of energy label since 2011.



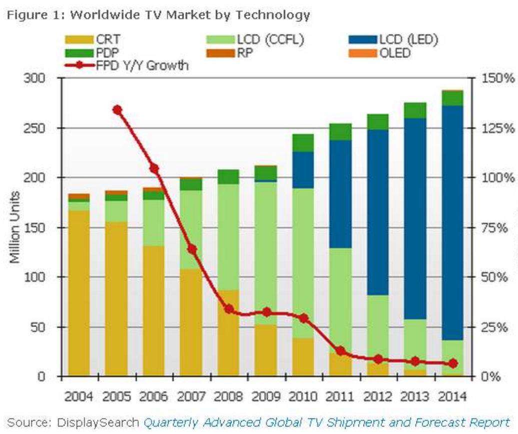


Figure 11: Evolution of monitored electricity consumption and sales (by technology) of televisions

Computer

The first large scale monitoring campaign of computers is quite recent (2007). As rate of laptop penetration has risen considerably in recent years (figure 12 right), the unitary consumption has rapidly and impressively decrease (figure 12 left).

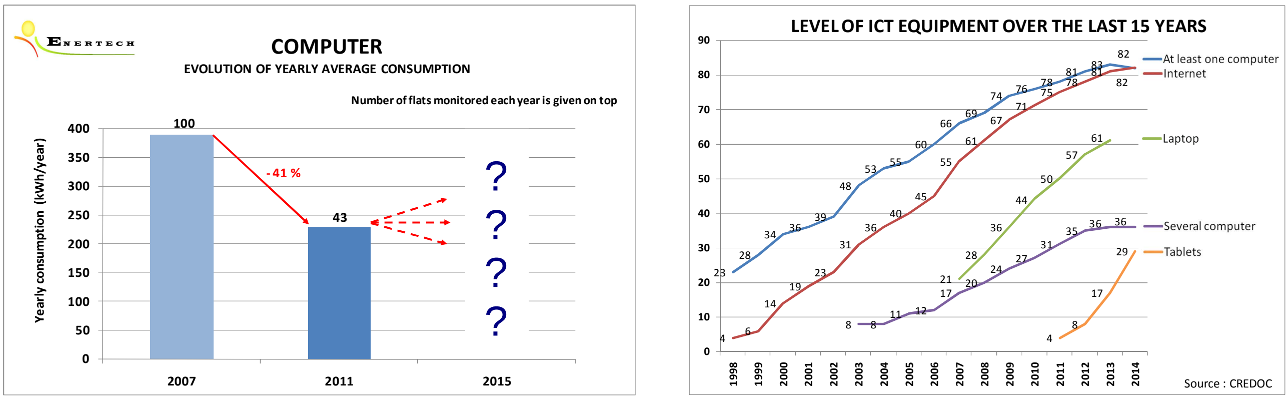


Figure 12: Evolution of monitored electricity consumption and level of equipment of computers

Washing machine

Between 1995 and 2007 decrease of consumption (figure 13) matched expectations due to technological improvement without major behaviour change. The actual average consumption is probably very different as the capacity of washing machine is drastically bigger nowadays.

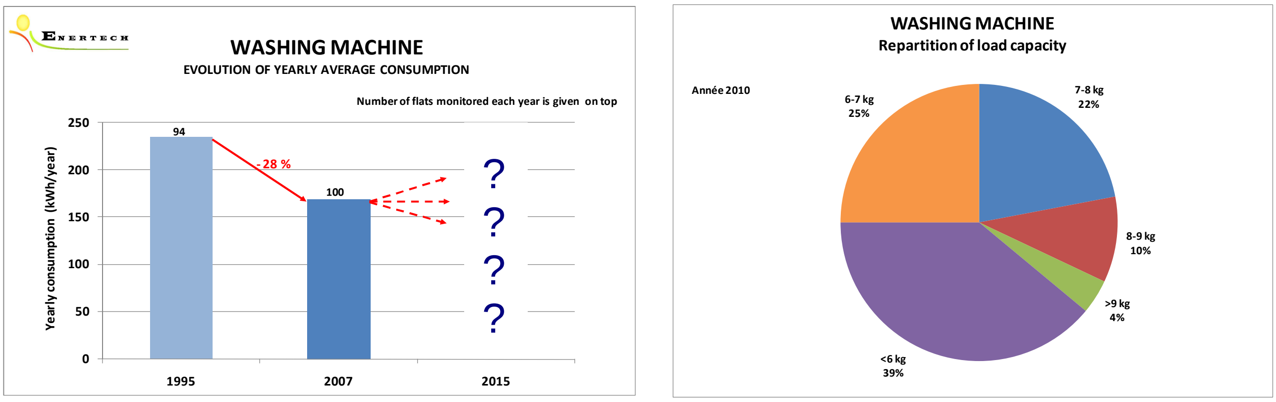


Figure 13: Evolution of monitored electricity consumption and size of washing machine (source of right graph: GIFAM)

Tumble drier

Unfortunately, no large scale on-site monitoring campaigns have been done on this very consuming equipment since the introduction of efficient appliances (heat-pump dryers).

Discussion

To sum up previous results analysis, on one hand we can predict that household electricity consumption will become the major issue to handle for residential sector, but on the other hand we underlined the structural lack of information and long-term evaluation on the subject, which affects the capacity to implement pertinent actions.

Ongoing performance monitoring is a prerequisite to understand how energy consumption changes and subsequently tailor and evaluate action.

Creation of a European Households' electricity consumption Observatory

Creating a European Households' electricity consumption Observatory would be absolutely necessary to give for each country a clear picture of level and distribution of electricity consumption. Only few monitoring campaigns have been carried out so far (EURECO, REMODECE…) and their results rapidly become outdated. Nobody knows precisely how the current electricity consumption of an average household is broken down or at what time of the day it is consumed. *There is a definite need of permanently up-to-date data.*

As a second step, the observatory could assess the impact of changes (technological and behavioural) enabling policy reorientation. The impact of predictable reinforcement of certain uses related to modern comfort and the introduction of new household equipment will thus be monitored upstream and will allow acting at an earlier stage. As penetration of new appliances or new habits is gradual, new trends are only visible on the basis of a dynamic analysis.

Feedback from the field should guide evolution of the European policy and funding opportunities. The understanding of the existing situation is a prerequisite for the design of future action levers.

As electricity requires a perfect matching in real time of supply and demand, a strong knowledge of load curve and maximum power demand is needed to size production, transport and distribution infrastructures. Anticipating changes is important to predict the need for upgrades of the entire chain.

Assess energy savings achieved through EuP directives

Numerous directives leading toward energy efficiency have been implemented during the last 20 years. The main recent and impacting ones are:

- Stand-by consumption limit of 1 watt since 2010, and 0.5 watt since 2013;
- Progressive phase-out of inefficient equipment (incandescent light bulbs, less efficient cold and washing appliances);
- Introduction of Energy Label for numerous equipments.

The previous examples highlight the lack of long-term evaluation of the concrete results of the legislative process and its potential adverse events. Permanent audit fieldwork should be done for each product subject to EuP directives.

A European Households electricity consumption Observatory would be a genuine strategic tool of evaluation and prospective. It would be a fundamental dynamic monitoring tool essential to assess actual savings realized thanks to EuP directives. One-shot assessment (short but also long-term) will remain necessary on specific trials (mainly raising awareness experiments).

An evaluation mission seems even more important for products only subject to voluntary agreements which do often not set stringent savings requirement. It is necessary to conduct a case by case assessment in order to check in which situation self-regulation is as efficient as compulsory policy.

Real on-site testing of the most innovative technical solutions foreseen by manufacturers, as already done in the former ECODROME project [13], will help assessing remaining technological savings potential and prevent possible problems.

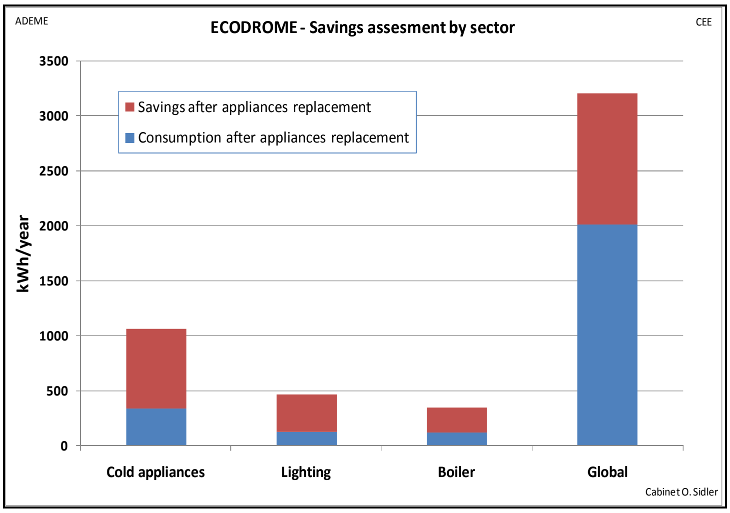


Figure 14: ECODROME – Monitored savings thanks to use of the most efficient equipment to date (1997)

But technologies actions plan will meet at one stage the limits and will not alone be sufficient to reach the goal of consumption reduction. To enhance effectiveness, it should come along with awareness actions.

Assess energy savings achieved through awareness raising actions

The ambition of reducing energy consumption means acting simultaneously on technologies and behaviours. Energy consumption depends as much on intrinsic characteristics of appliances as on financial, cultural (environmental concerns), sociological (comfort requirement) and psychological (ability to understand equipment features) drivers. Consumption patterns also depend on lifestyle.

Numerous experiments with behavioural incentives emerge in Europe. Most of the actual awareness raising actions evaluations (where they exist) do not last long enough. Long-term relevant assessments are necessary in order to find out the most efficient behavioural incentives. Analysis should especially be focusing on monitoring sustainability issues. Benefits can indeed disappear after the first months. One should learn from these first experiments and set up from the start of each project a consistent and long-term monitoring program. It holds particularly for new innovative awareness raising projects funded by European Horizon 2020 (for example for feedback systems concrete impacts).

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Monitoring the energy consumption of fridge-freezers and washing machines of a sample of households in Northern Italy

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Abstract

The energy efficiency class and the indication of the annual energy consumption (included in the energy label) are renowned indicators and represent useful references suitable to compare different models, but the actual electricity consumption of domestic appliances may depend on several different factors. Among these, the behaviour of the final user that may considerably affect the actual consumption and that can hardly be taken into account when performing standard tests applied to the energy labelling of a product. In order to clearly identify the real performances of installed appliances and the impact of energy standards it is therefore important to implement on-site measurement campaigns.

For this purpose a recent measurement campaign involving 20 households in Northern Italy has been carried out. The electricity consumptions of cold appliances and washing machines have been monitored for approximately 5 weeks. The main results present the daily absolute electricity consumption and the difference between actual consumptions and labelled values, as well the temperatures and the frequency of washing cycles for washing machines.

The data collected have been compared to the results of previous campaigns carried out in Italy in the early 2000's. The main results of the comparison are: i) the average energy consumption of cold appliances is substantially lowered; ii) the cold appliances older than 15 years show the higher consumptions; iii) regarding washing, energy consumption of colder cycles is increased, while energy consumption of the 60°C cycle is decreased; iv) the behaviour is substantially changed, colder cycles are now more frequently used.

Keywords: household appliances, energy monitoring, user behaviour.

Introduction

In the latest years, the international regulation has been focused on the energy performance of the domestic appliances, as they represent significant proportions of total energy consumptions. In the EU, the enforcement of energy efficiency policies found its origin in the definition of a common energy labelling scheme and in the introduction of minimum energy performance requirements (Ecodesign). These two approaches – which are intended to contribute to a primary energy use reduction of 25% by 2020 – are now governed by two revised[1] Directives on energy efficiency policies: Directive 2010/30/EU [1] on Energy labelling and Directive 2009/125/EC [2] on Ecodesign.

There is clear evidence[2] that the energy efficiency policies to the white appliances sector have provided a significant impact on energy savings of the considered products. The success is due to a

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[1] Both directives were new versions of already existing directives (directive 92/75/EEC and 2005/32/EC).

[2] The impact was first demonstrated in the Monitor I, II and III studies which produced an extensive model by model sales database for a variety of labelled products.

combination of EU legislation, national programs (e.g. in Italy Tax deductions and White Certificate scheme) as well as the old voluntary agreements among manufacturers and "business as usual" technical development. In previous years it was estimated [3,4] that impact of policies adopted between 1995 and 2005 produced a total of 65-75 TWh/year savings. More recently [5], the impact of the Ecodesign measures was an additional 8 TWh/year for domestic refrigeration and 1,5 TWh/year for washing machines. 15% of washing machines, 10% of dishwashers and more than 50% of cold appliances sold in early 2011 were located reported an energy class higher than A [5]. This evidence proves the success of the energy label as to white appliances.

On the other hand it is interesting to observe that the residential electricity consumption of the European households is still rising. “Between 1990 and 2010 final residential electricity consumption grew by 31.92%. In the year 2010 the consumption level of electricity by households in the EU-27 reached with 842 663 GWh its highest point since 20 years.” [5] During the last decades although all appliances have become more efficient, the number[3] and size[4] of dwellings and appliances per dwelling[5] have increased. Moreover many appliances have more functions or special features that require more energy, and above all they are used more often and for longer periods of time resulting in a significant increase in consumption[6]. In accordance with the ODYSSEE Italian indicators[7] the increase of the equipment ownership caused an additional electrical consumption of 33 TWh over the period 2002-2012.

For this reason it is crucial to perform studies finalised at a better understanding of the development of the user’s behaviour and of the real trends of appliances’ consumption. In Italy few measurements have been carried out in recent years. The monitoring activities of the European projects EURECO [6] and REMODECE [7], as well of the national project MICENE [8] are the main examples of direct measurement of electrical energy consumption from selected household appliances, operating under real life conditions.

In 2000-2001 the EURECO project monitored almost 400 European households (100 in Italy). The campaign gathered data of electric consumption of the main domestic appliances. The measurement campaigns lasted one month in every household. A detailed questionnaire was also used to survey the participants. EURECO project, in particular, monitored every single source of light in the households. In 2002-2003 the MICENE project enlarged the scope of the EURECO Campaign in Italy, monitoring the consumption of the main electric appliances in ten households during six consecutive months.

In 2006-2008 the REMODECE project fulfilled specific measurement campaigns in order to enlarge the data availability in twelve EU countries. The measurement campaigns were carried out as a light measurement campaign, focusing on new electronic loads, standby consumption and lighting. 1300 European households were monitored, and 12.310 single appliances measured. In Italy detailed intrusive audits were accomplished in 60 households.

Methodology

On site operating conditions may alter significantly the performances of the appliances. Measurement campaigns evaluating real consumption in households are difficult to perform but allow a better understanding of the real impact of the introduction of more efficient appliances.

Latest available data for Italy date back to 2003. For this reason in late 2013 a new measurement campaign was started, by involving 20 households in Northern Italy. The monitoring activity was

[3] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=lfst_hhnhtych

[4] http://www.eea.europa.eu/data-and-maps/figures/drivers-of-the-change-in-2

[5] http://www.odyssee-mure.eu/publications/efficiency-by-sector/household/Household-profile-37.pdf

[6] http://www.odyssee-mure.eu/publications/efficiency-by-sector/household/Household-profile-33.pdf

[7] www.indicators.odyssee-mure.eu/decomposition.html

focused on the energy consumption of refrigerators (17 appliances) and washing machines (14 appliances) and it lasted about five weeks, from 17th December 2012 to January 21st, 2013. This period covered normal working weeks (the first week and the last two ones) and a vacation period correspondent to the Christmas holidays (the second and third week). The sample object of the survey was not chosen on statistic basis but has roughly the same characteristics as those analysed in previous monitoring campaigns (see below).

A plug-in energy meter (Parsimonio by Orieme) with display has been used for the monitoring, focused on fridge-freezers and washing machines. After connecting the monitoring instruments to the main appliances, the families simply had to read and transcribe into an ad-hoc template the value reported by the display of each meter. As to fridge-freezers, the daily reading of the meter was made at one and the same time, whereas for the washing machine, the report was made at the beginning and end of each washing cycle.

Table 1 – Main technical features of the used wattmeter.

Power supply	230 Vac, 50 Hz
Maximum power load	16 A / 3680 W
Energy meter	0 – 9999,9 kWh
Power measurement accuracy	+/- 1,5%
Electricity consumption	< 0,5W

The final data are obtained combining (1) the results of the surveys filled in by the samples of families which participated in and (2) by the estimation of the general consumption of the houses arising from the reading of the meter at the beginning and at the end of the considered period. Each family had to complete a questionnaire, presented in Table 2. In addition to technical data (manufacturer, model, age and energy class), the questionnaire regarding the monitoring campaign of the use of the washing machine aimed to analyse the user's habits: the weekly washing cycles and the percentage of use of full load and/or partial load. A selection of programs was reported and the relative percentage of the most used programs requested (prewashing, cold wash, woollens, delicates, coloureds, cotton in terms of temperature and level of soil).

Table 2 – Data collected through the questionnaire.

Family composition (for each member)	Gender
	Age
	Presence (continuous, daily, occasional)
Household total electrical consumption	Meter readings at the start and at the end of the campaign (divided by contractual time bands)
Cold appliance data	Type (refrigerator, fridge freezer)
	Manufacturer, model
	Age
	Energy class
	Star rating
	Free standing or built in installation
	Heat sources proximity
	Volume (gross and net volume of each compartment)
	Number of thermostat
	Manual or automatic defrosting
Washing machines	Front or top loading type
	Manufacturer, model
	Age
	Energy class
	Free standing or built in installation
	Number of cycles per week
	Typical use (full load, half load)
	Typical programme (temperature and fabric)

Results

Household electricity demand

The daily total electricity consumption of considered households was estimated dividing the consumption recorded by the general meter by the number of days of monitoring. Only data by 14 households were considered fairly consistent and were included in the figures reported below: Figure 1 shows the values resulted and Figure 2 reports daily consumption per capita (taking into account only family members with continuous or daily presence). In none of the households space heating and water heating are provided by electricity.

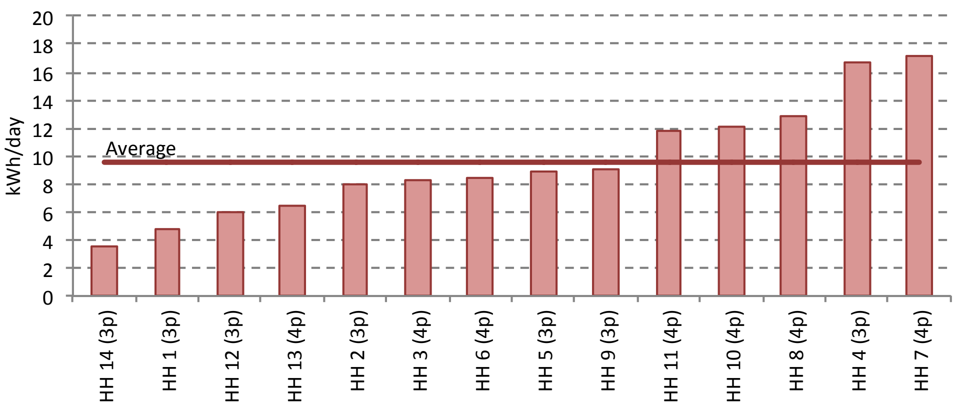

Figure 1 – Total household daily electricity demand

Although it was not possible to collect actual data from the energy bills, an estimation of the annual consumption is provided in order to develop a rough comparison with the results of previous campaigns.

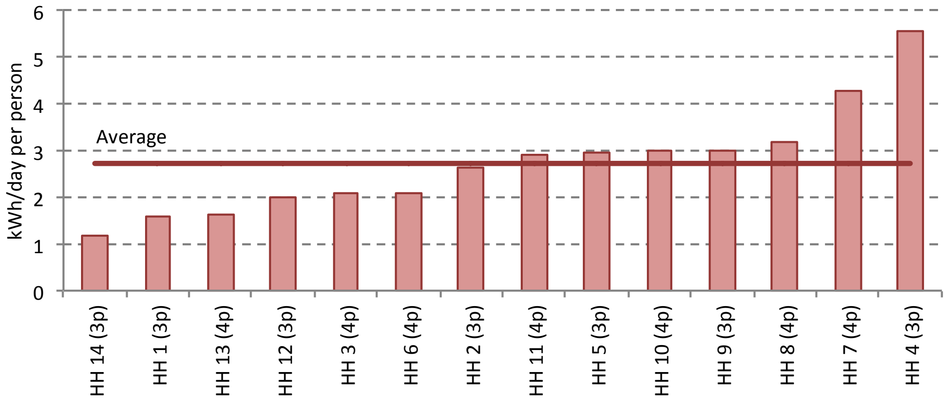

Figure 2 – Daily electricity demand per person

The average annual electricity consumption of households (calculated as the daily data multiplied by 365) is equal to 3491 kWh/year (min. 1283 kWh/year; max. 6254 kWh/year). The average electricity consumption per capita is 996 kWh/year (min: 428 kWh/year; max: 2031 kWh/year). These figures are a fairly rough estimation. To calculate the real annual data, the seasonal variation of electric consumption should have been taken into account.

Energy consumption of fridge-freezers

Data from 17 different fridge-freezers were collected and analyzed. Considering the energy label, 13 out of the 17 families included (76%) were equipped with fridge-freezers in the highest energy classes (Class A and above), two of them (12%) own cold appliances classified in lower energy classes (Class B and C). In two cases, corresponding to about 12% of the sample, energy class is unknown as the appliances are older than 15 years (Figure 3).

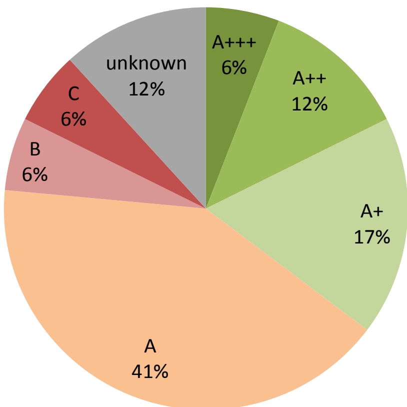

Figure 3 – Energy label class of monitored Fridge-freezers

Consumption during the usage is closely correlated to the energy class, but in some cases the influence of the usage (number of door opening, storage of hot food, etc.) on the energy performance is remarkable, as reported in Figure 4. The annual consumption is simply calculated multiplying by 365 the average daily consumption monitored during the campaign. This probably represents an underestimation of the real annual consumption, because only winter days were monitored in the measurement campaign. The consumption during summer days is expected to be higher, due to the higher ambient temperatures. A six months campaign should be organized in order to have a clear measurement of the seasonality of the actual consumptions.

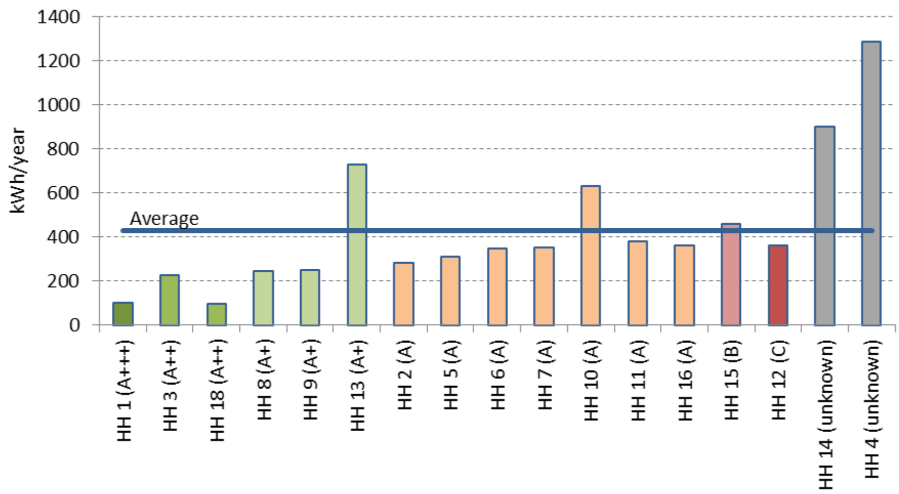

Figure 4 – Estimated annual electricity consumption of monitored fridge-freezers

During the campaign, fridge-freezers represent 12.7% of the total electricity consumption of households, with a percentage maximum of 37% and a minimum of 5.4% (Figure 5). This percentage varies depending on the specific consumption of the appliance (the majority of efficient appliances report low level of relative consumption), but it is also strictly affected by the number of electrical devices connected to the same general meter, to their energy efficiency and the habits of each family.

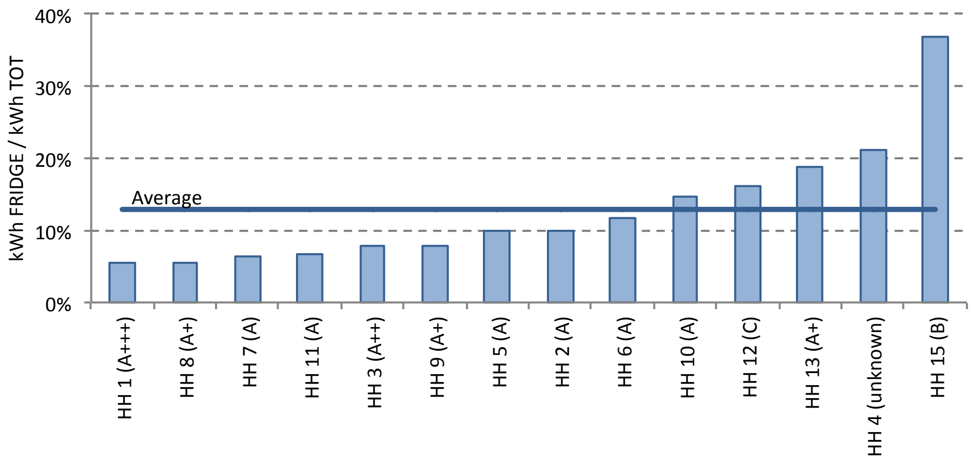

Figure 5 – Estimated annual fridge-freezers consumption compared to the total electricity consumption in households

For seven fridge-freezers the labelled consumption data were available. Actual and labelled consumption are shown in Figure 6. The differences between the actual and labelled consumption range is between -36% and +85%, showing the importance of real on-site conditions. In most cases the actual consumption is slightly lower than the labelled one. This may be caused by the fact that the labelled consumption is measured with an ambient temperature of 25°C, while during the winter season the temperature in the kitchen is considerably lower (normally around 20°C). Other real use conditions may increase the actual consumption (door openings, proximity to heat sources, built-in installation) but in most cases they are not enough to compensate the difference of ambient temperature. However on average the difference is only +2% thanks to the performance of the A+ fridge freezer in household 13 which is 85% higher than expected. The average difference of the sample excluding HH13 is -16%.

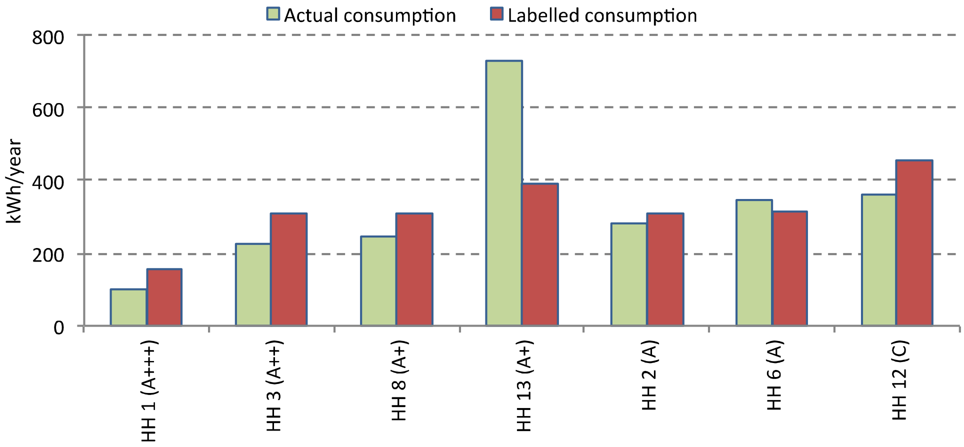

Figure 6 – Actual and labelled annual consumption for sample fridge freezers

From the economic point of view, in case of general meters with committed capacity of 3 kW, the marginal cost for 1 kWh depends on the total consumption of the house (€ 0.149 for a home consuming less than 1740 kWh per year, € 0.230 for consumption between 1800 and 2580 kWh, € 0.321 for consumption between 2640 and 4380, € 0.343 for a consumption higher than 4440 kWh, according to the Energy Authority tariffs in late 2013). From this figures we can estimate the total annual expenditure related to the domestic cold appliances, shown in Table 3.

Table 3 - Annual energy consumption and costs for sample fridge freezers

Sample fridge-freezers	Energy unit costs	Annual consumption	Annual energy costs
	€/kWh	kWh/year	€/year
HH 1 (A+++)	0,230	100	23,02
HH 3 (A++)	0,321	225	72,19
HH 9 (A+)	0,343	254	87,23
HH 5 (A)	0,321	313	100,54
HH 15 (B)	0,321	475	152,32
HH 14 (unknown)	0,343	901	308,95
HH 4 (unknown)	0,343	1290	442,63

Energy consumption of washing machines

Data from 19 different washing machines were collected during the measurement campaign. Eighteen out of nineteen monitored washing machines (95%) belong to higher energy classes (A and above). Only one appliance out of nineteen is not an energy efficient model; it is a very dated appliance, purchased about 20 years before, and so devoid of the energy class (Figure 7).

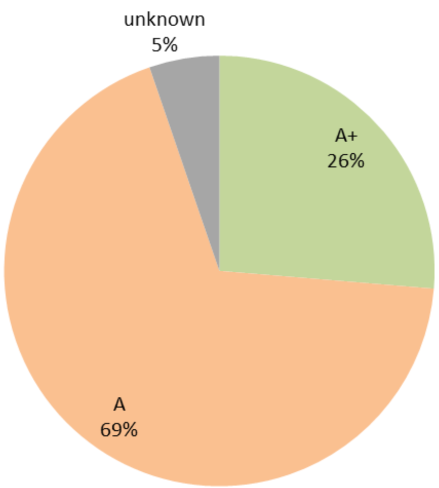

Figure 7 – Energy label class of monitored washing machines

On average, the analysed families made about 17 washing cycles per month (the range is between 2 and 55), equivalent to about 200 washings per year. But the number of washing cycles is expected to depend on the number of people living in the considered household. In terms of per capita, on average, the families analysed made about 7,0 washing cycles per person per month (the range is from a minimum of 1 to a maximum of 18), equivalent to about 84 washings per person per year (Figure 8).

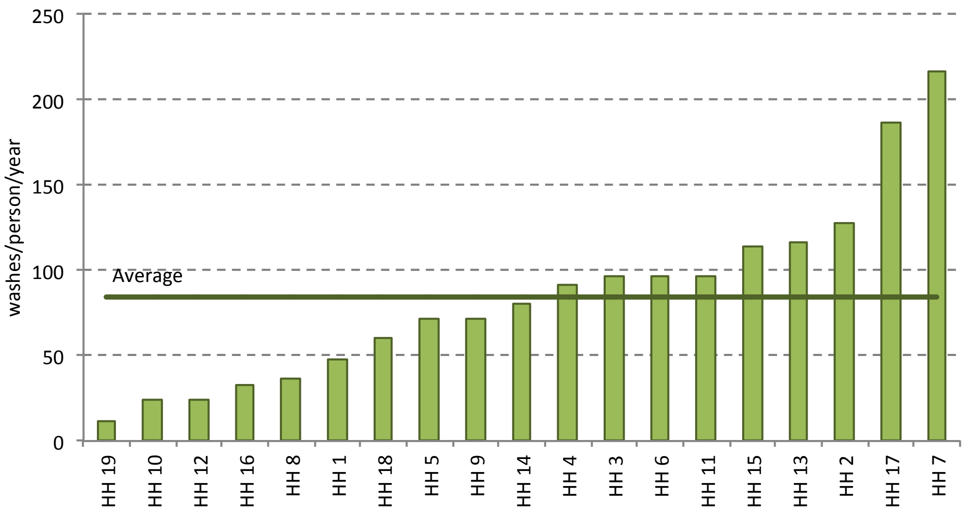

Figure 8 – Estimation of annual washing cycles per person

Figure 9 shows the average consumption of the analysed washing machines calculated multiplying by 365 the average daily consumption monitored during the campaign. The average value is 203 kWh/year, about half of the average contribution of fridge-freezers. The total contribution of these appliances compared to the overall consumption of the household is on average 5.4%, with a minimum of 0.2% and a maximum of 13%.

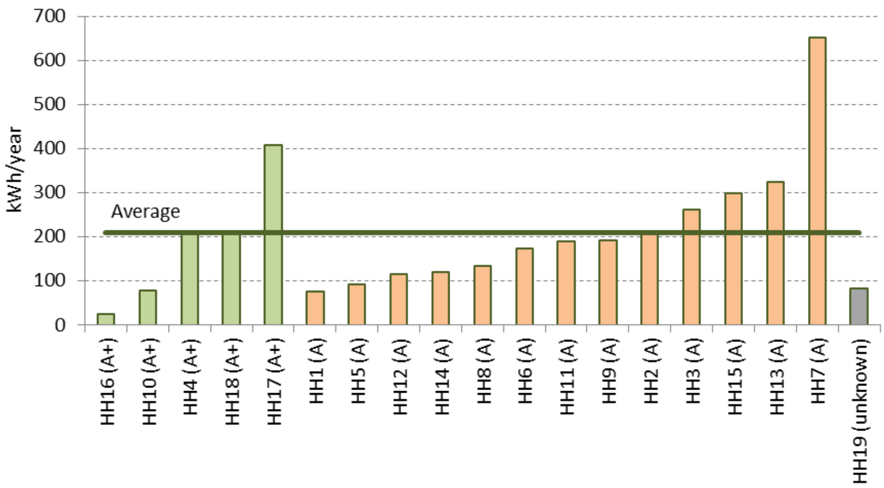

Figure 9 – Estimated annual consumption of the washing machines

The annual consumption of the single washing machines depends largely on the number of washing cycles. For example, the 20 years-old washing machine shows a small annual consumption, because of the low usage frequency. Therefore in the following figures and tables the total annual consumption has not been taken into account. Shown consumption data are referred to the single washing cycle or to an annual frequency that is equal for all the considered washing machines.

Taking into account a total of washing cycles (made during the monitoring period) equal to 480, Figure 10 highlights that the cycles most used are at 40°C (188) followed by, in decreasing order, those at 30°C (165), 60°C (85), cold washing cycle (30), washing cycle at temperatures higher than 60°C (5) and finally cycles at 50°C (4). The simple rinsing and extraction programs, have been used only once each.

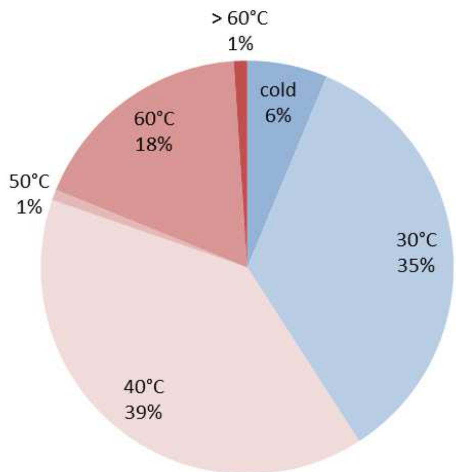

Figure 10 – Number of washing cycles per temperature

Grouping the washing machines by declared energy label and disaggregating the data by temperature of washing cycle, the average consumption for washing have been evaluated and shown in Figure 11. The 50°C and > 60°C categories data represent only a small amount of washing cycles. Furthermore, the 20 years old washing machine (with unknown energy class) was used only for 4 cycles at 30°C. The value shown in the grey column is therefore not statistically relevant. The water temperature in the supply network is between 8 and 10°C.

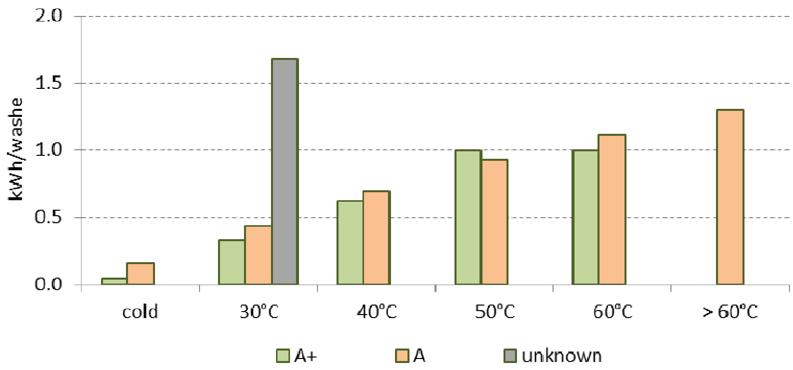

Figure 11 – Energy consumption per energy class and washing cycle

Figure 12 shows the average consumption per washing cycle with indication of the different types of fabrics washed.

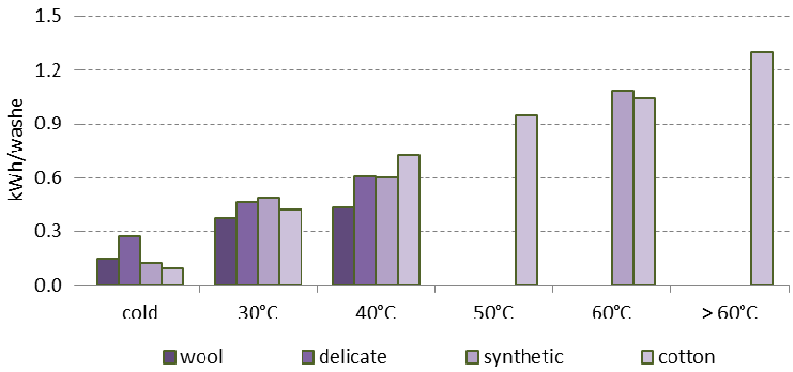

Figure 12 - Average consumption per temperature and type of fabric

Figure 13 reports the evaluation of the annual energy consumption referring to an independent washing machine indicator, obtained on the basis of the new labelling scheme[8] and considering a tolerable error margin (based on the lack of data and the qualitative value of some information provided by the 10 families that we considered most reliable). The estimation didn't consider the OFF and LEFT ON mode, as foreseen by the labels. For evaluating the SAE_C (the standard annual energy consumption) the value of the washing machine (the factor "c" in the formula) has been kept constant and equal to 5 kg for all washing machines. The average consumption is 188 kWh/year, ranging from a minimum value of 157 kWh/year to a maximum of 233 kWh/year.

[8] Annual energy consumption is based on 220 standard washing cycles for cotton programs at 60°C and 40°C, at full and partial load. In particular the weighted average is calculated on 3 cycles at 60°C full load, 2 cycles at 60°C half load and 2 cycles at 40°C half load.

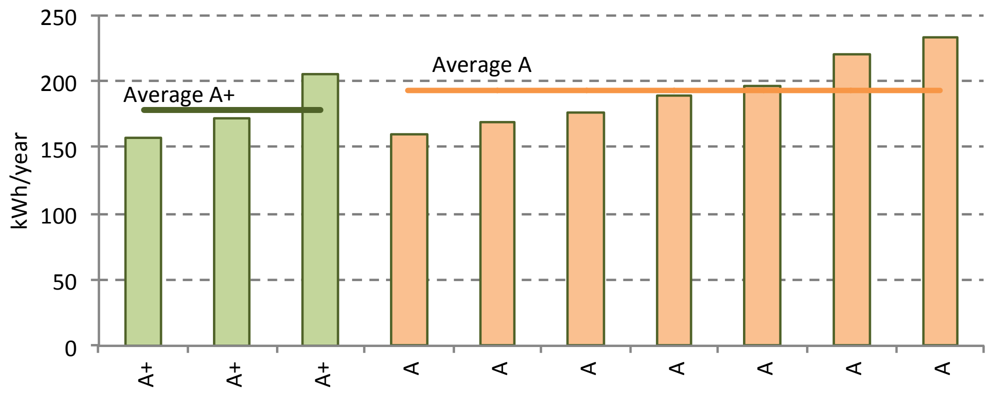

Figure 13 – Calculated annual energy consumption applying the new energy label methodology

It must be highlighted that the washing machines included in the campaign were all labeled in accordance with the previous methodology taking into account only the standard 60°C washing cycle consumption. By applying the new methodology the class “A” washing machines would show an annual consumption between 161 and 233 kWh, with an average of 192 kWh. The new label class “A” consumption range is between 197 and 226 kWh. The class “A+” washing machines would show an annual consumption between 157 and 205 kWh, with an average of 178 kWh, while the new label class “A+” consumption range is between 174 and 196 kWh.

In summary the average values are not far from the new label consumption range both for class “A” and class “A+” washing machines. The new label gives however a better snapshot of the real annual consumption, and is a more effective instrument to highlight the differences among different washing machines.

Contextualization of the results

Towards the contextualisation of the conducted analysis, the achieved results have been compared with the outcomes of similar studies developed in the past: the EURECO project, co-funded by the European Commission in January 2002 [6] and the MICENE project (measurements of electric energy, [8]) performed by the Department of Energy of the Polytechnic of Milan in September 2004, monitoring the energy performances of 72 fridge-freezers and 96 washing machines.

In agreement with several sectorial analysis (quoted in the introduction), this comparison has highlighted that while the energy efficiency of equipment and domestic appliances has increased in recent years, the annual energy consumption of reference households has grown over the years. In our case the difference amount to 334 kWh corresponding to an increase of 30 kWh/year, for each family with respect to 2002, and 262 kWh (or 29 kWh/year) compared to 2004.

Table 4 - Annual household electricity consumption as estimated in different campaigns (data for Italy)

2002 EURECO Campaign	2004 MICENE Campaign	2013 Current campaign
3157 kWh/year	3229 kWh/year	3491 kWh/year

As a result of recent technological developments, the minimum and average annual consumption of fridge-freezers has substantially dropped (Table 5).

Table 5 – Electricity consumption of fridge-freezers as measured in different campaigns (data for Italy)

	2002 EURECO Campaign	2004 MICENE Campaign	2013 Current campaign
Average annual consumption	629 kWh/year	637 kWh/year	409 kWh/year
Maximum annual consumption	1232 kWh/year	1213 kWh/year	1285 kWh/year
Minimum annual consumption	328 kWh/year	328 kWh/year	100 kWh/year
Average per capita consumption	191 kWh/year	191 kWh/year	129 kWh/year

The washing habits have changed significantly, with a reduction of selected washing temperatures (Figure 14).

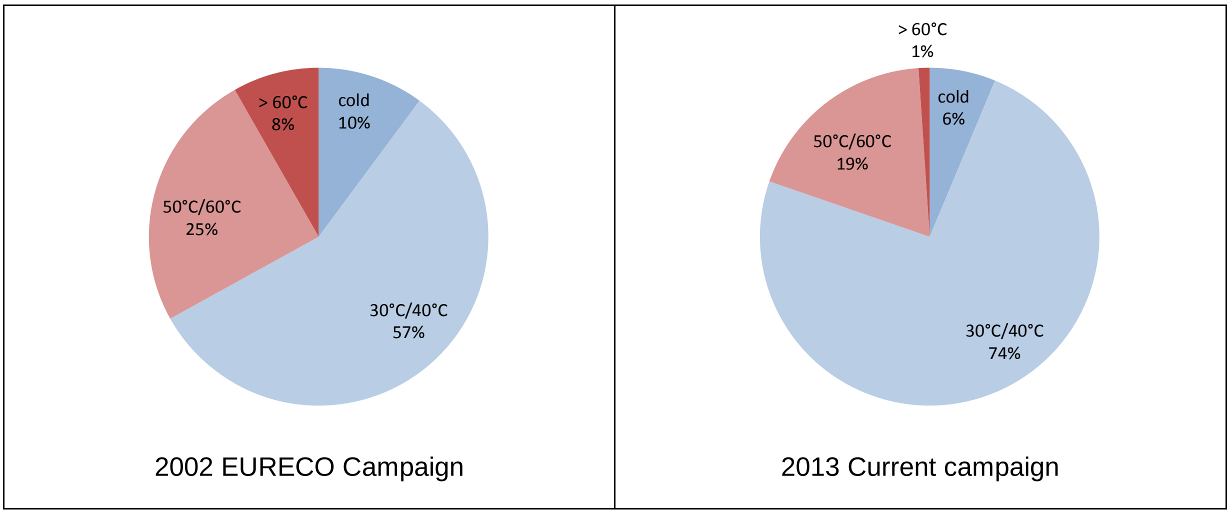

Figure 14 – Number of washing cycles per temperature as measured in different campaigns (data for Italy)

Nevertheless, the annual consumption of washing machines has not been reduced in a particularly sensible way compared to the previous decade (Table 6). Probably this trend is due to the increase in consumption of low temperature washing cycles (Table 7), in turn caused by increased average load capacity that has increased from 5 kg in previous campaigns to 5.6 kg (+ 12%) in the current campaign.

Table 6 – Electricity consumption of washing machines as estimated in different campaigns (data for Italy)

	2002 EURECO Campaign	2004 MICENE Campaign	2013 Current campaign
Average annual consumption	211 kWh/year	224 kWh/year	200 kWh/year
Maximum annual consumption	544 kWh/year	n/a	649 kWh/year
Minimum annual consumption	n/a	n/a	25 kWh/year
Average per capita consumption	57 kWh/year	n/a	55 kWh/year

Table 7 shows the specific electricity consumption of an average washing cycle depending on the cycle temperature.

Table 7 - Electricity consumption of washing cycles depending on cycle temperature as measured in different campaigns (data for Italy)

	2002 EURECO Campaign kWh/cycle	2013 Current campaign kWh/cycle	difference
Cold cycles	0,149	0,157	+5%
30°/40°C	0,497	0,566	+14%
60°C	1,097	1,061	-3%
90°C	1,800	1,300	-28%

Energy consumption of cold cycles and of 60°C cycles is quite stable (+5% and -3% respectively). Energy consumption of 90°C is substantially decreased but, given the small sample of 90° cycles, it is not possible to draw any conclusion. The more interesting result in this table is the +14% increase in the energy consumption of the 30-40°C cycle. In the energy label adopted until 2010, the 30-40°C degrees cycle were not included in the evaluation of Energy Efficiency Index until 2010. For this reason the manufacturers had no incentive to increase their efficiency: therefore a +12% increase in the average capacity has led to a +14% increase in the consumption.

The total annual consumption of washing machines depends on the number of cycles, the washing temperatures and on the washing machine efficiency. If we consider the standard 220 annual cycles, it is possible to compare the effects of the appliance efficiency and of the washing frequency on the annual consumption. In Figure 15 a comparison of four different scenario combining 2002 and 2013 cycle consumption and frequency is shown. The effect of the behavioral changes is larger than the effect of the increase in the appliances efficiency.

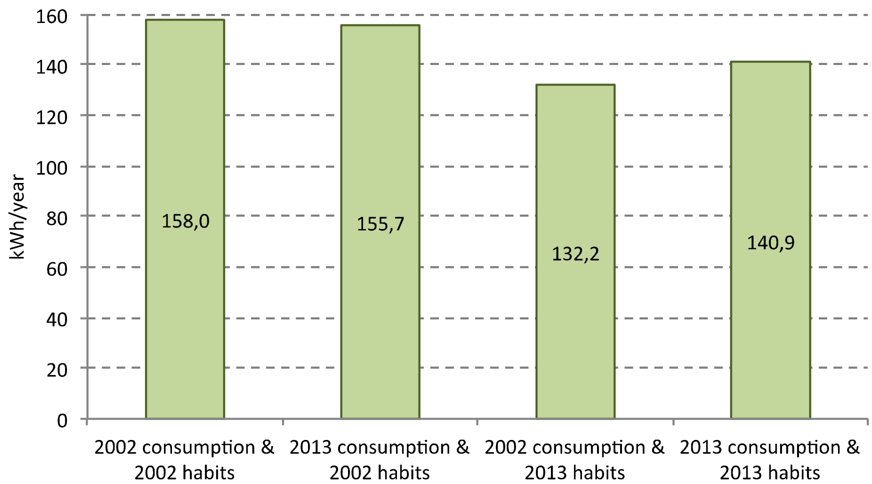

Figure 15 – Annual household consumption for 220 washing cycles in different scenarios.

Conclusions

A recent measurement campaign has been developed, involving 20 households in Northern Italy. The electric consumptions of cold appliances and washing machines have been monitored for approximately 5 weeks. Although the sample is not statistically relevant, the data collected show interesting trends when compared to those collected in previous measurement campaigns (e.g. EURECO and MICENE projects 2002-2004), where most appliances monitored were sold and installed before the introduction of the energy label (1998).

Given the small samples size, it is not possible to draw quantitative conclusions, but general information on the actual trends. The main results of the comparison are:

- the average energy consumption of the appliances is substantially lowered: -36% for the fridge freezers and -11% for the washing machines, when compared to the MICENE indicators.
- The cold appliances showing high consumption are the older than 15 years ones: in our sample, the average of their annual consumptions were three times higher than the average of the annual consumptions of the labelled appliances (class C included). This is due to the low starting efficiency and the decay due to the age.
- The average energy consumption of a washing cycle shows smaller differences, in particular energy consumption of cold cycles and of 60°C cycles is quite stable (+5% and -3% respectively), while energy consumption of the 30-40°C cycle is increased .(+14%) probably because these cycles were not included in the Energy Efficiency Index until 2010 (therefore a +12% increase in the average capacity has led to a +14% increase in the consumption);
- A substantial change of user behaviour was observed: colder cycles are now more frequent than 10 years ago (+13%) and the cycles at temperature higher than 60°C are no longer used. This is probably due to the improvement of the washing quality at low temperatures, that in recent appliances is often achieved through the extension of the mechanical phase.

Further measurements may be foreseen in order to define a more robust sample. In particular we aim to extend the experience to other households for longer monitoring periods and during different seasons. It would then be interesting to integrate the simplified ("self-made") monitoring approach here presented with detailed measurements for shorter periods. These latter should include the possibility to monitor complementary parameters, as the temperature in the kitchen and inside the fridge, the number of openings of fridge doors and the duration of the washing cycles. To this purpose a low-budget monitoring kit is under design and we are building the first prototype based on the Arduino platform.

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A refined baseline methodology for large scale lighting retrofit projects

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Abstract

The residential sector is one of the major consumers of energy produced in the world. According to International Energy Balances (IEA, 2013), the residential sector demand represents about a quarter of the primary energy used in the world. Therefore, most energy efficiency programmes targeting large savings on a national or regional level pay particular attention to the opportunities in the residential sector. Lighting retrofitting on a large number of sites constitutes one of the most used strategies of energy conservation in the residential sector. However, given the large number of sites involved in this type of project, conventional measurement and verification (M&V) techniques based on the audit of each site, are not cost effective. Often, a statistical assessment approach based on the audit of a limited number of sites is the methodology used to mitigate the cost and the logistical challenges associated with the project. The major challenge in projects of this nature is to accurately estimate the energy consumption of a large number of sites using the measurement performed on a sample of sites selected from the overall population. In this research, baseline methodologies used in a selected number of light retrofitting projects have been analysed and, based on the observations made during this analysis, some improvements are suggested. The proposed methodology has been tested on a number of residences located on the premises of the University of Johannesburg. This paper describes the existing baseline methodologies and presents the improvements suggested to enhance the credibility of M&V results. The key results of the experimental phase of this project are also presented in this paper.

Introduction

The residential sector is a major consumer of the energy generated in the world (IEA, 2013) and lighting retrofit programmes constitute a powerful tool for tapping into the energy saving opportunities in the residential sector (Jackson & Vanderpuije, 2000; NREL, 2013). Therefore, energy conservation measures implemented in this area may result in significant savings. However, a particular measurement and verification (M&V) approach is required to determine the performance of this type of project. The conventional M&V techniques based on individual site surveys are not feasible in this context because of the large number of sites involved in such projects. In South Africa the approach used consists of auditing a sample of sites and extrapolating the result to the overall population. Richman recommends that 10% of the overall population should be audited once a year to assess the sustainability of the performance (Richman, 2012). The main purpose of this research is to propose a method for evaluating the accuracy of the results obtained by auditing a sample.

Baseline methodology for large scale lighting projects in South Africa

Description of the methodology

The assessment method used to establish the baseline consists of surveying a small number of sites deemed to be representative of the overall population and then generalizing the results obtained from the sample. The methodology used to determine the sample size is based on Cochran's Formula below:

$$\boldsymbol{n} = \frac{\boldsymbol{z^2} \times \boldsymbol{cv^2}}{\boldsymbol{e^2}}$$

where **n** is the sample size, **z** is the desired confidence, **e** is the desired precision and **cv** represents the coefficient of the variation of the population (EVO, 2010; Cochran, 1977). During surveys auditors focus on the determination of the key parameters as recommended by the EVO and SANS standards (EVO, 2014; SANS 50010). In lighting retrofit projects, the operating hours, number of fixtures and power draw per fixture are considered as the key parameters (NREL, 2013). All these parameters are usually given by the project developer (ESCo). The site survey is therefore conducted on a small random sample to confirm the accuracy of the information provided by the project developer. Based on the survey results, the evaluator can either decide to use the information provided by the project developer or adjust these figures with a factor to reflect results observed during the survey. After collecting all these parameters, the baseline energy can be calculated using the following formula:

$Daily\ baseline\ energy = Number\ of\ fixtures \times Daily\ operating\ hours \times Power\ draw\ per\ fixture\ (1)$
(DOE, 2008)

Using the operating hours collected from the survey, it is also possible to develop an average demand profile by determining the percentage of the load that is being used during each specific period of the day.

Table 1 illustrates how the daily profile will be determined.

Table 1: Daily profile based surveys

Time	*Total installed capacity (kW)*	*% of lights on*	*Power usage kW*
00:00	600	100	600
02:00	600	60	360
04:00	600	60	360
06:00	600	50	300
08:00	600	35	210
10:00	600	35	210
12:00	600	35	210
14:00	600	35	210
16:00	600	35	210
18:00	600	100	600
20:00	600	100	600
22:00	600	100	600

Errors associated with the baseline methodology

A baseline developed from extrapolated information will have inherent errors relating to the nature of the data collection process that was used. It is therefore the responsibility of the M&V practitioner to mitigate these errors and keep them at an acceptable level. These errors represent a risk for the project, especially if incentives are paid based on the reported performance. The following types of errors should be considered when using this approach: sampling errors, human errors and instrument errors.

Sampling errors are related to the size of the sample. The level of accuracy of the results from a sample survey depends on the ratio between the size of the overall population and the sample size. Although, the IPMVP (EVO, 2010) provides a clear method for determining the optimal sample size, budget constraints often force M&V practitioners to use a sample size that is suitable for the budget and provides valuable results (GSEP, 2014).

Human errors usually affect the equipment inventory during the site audit because it is easy for installers and auditors to lose the count when dealing with a very large number of lights. Operating hours also constitute a parameter that can be very sensitive to human error, especially when interviews are used as the data collection method. It can be difficult for people to accurately remember the operating hours of lights in certain areas (Theletsane, Coetzee & Grobler, 2007), and since operating hours are obtained through questionnaires, the accuracy of the answers should be assessed. Note that in all the lighting retrofit projects reviewed as part of this research, the operating hours are determined through questionnaires. In South Africa data loggers are often avoided in order to mitigate the M&V costs.

Instrument errors result from the built-in inaccuracies of instruments that are used for spot and/or laboratory measurements. Such errors are usually manageable because they are specified by the manufacturer and can be considered in the calculations.

Proposed improved methodology

The integration of a validation phase was suggested in order to evaluate the accuracy of the results obtained from the survey. This phase consists of monitoring the energy consumption of a few sites (number lower than sample size) and comparing the metered results with survey-based results. Based on the difference between the two, the evaluator can either choose to refine his approach or use the survey results as they are. In the next section of this paper, the implementation and results of such tests are presented for illustration purposes.

Case study: Sophiatown residence in Johannesburg

Description of the test phase

The methodology suggested was applied to the University of Johannesburg unisex student residence named Sophiatown. The residence consists of single dormitory rooms and common areas which include kitchens, communal bathrooms and passages (corridors). The methodology was implemented in two phases, the first phase being the metering phase and the second phase a survey phase.

For the metering phase, data loggers were installed in the distribution board of the student residence. The loggers were placed on the circuits that feeds a number of dormitory rooms and common areas (passages, kitchens and bathrooms).The monitored areas included 48 dormitory rooms, 5 passage ways, 3 communal toilets and 2 kitchens.

During the survey phase, the research team interviewed 18 students residing at Sophiatown. Using a questionnaire, the operating hours and number of lights in a dormitory were obtained. An on-site audit was conducted to determine the number of fixtures per area and the power drawn by each fixture.

Results of the test phase

Table 2 presents a summary of the data collected from the interviews with the residents.

Table 2: Sophiatown residence dormitory and common area lighting data

Areas	Number of areas	Number of lights	Power (W)	Average operating hours (h)
Passage	5	8	12	24
Toilet	3	6	12	24
Kitchen	2	2	36	24
Rooms	48	3	28	8.8

Table 2 illustrates that the average number of operating hours per room is 8.8. According the interviewed students, the lights located in the common areas are on at all hours (24 hours) whereas the operating hours of dormitory lights vary from one room to another. A load profile was developed based on the survey results. The latter information allowed the research team to develop the average daily profile of electricity consumed for lighting usage as presented in Figure 1. Based on the information collected from the respondents (operating hours, number of fixtures and wattages) total energy consumed per day was found to be 55.66 kWh. The average daily profile is presented in Figure 1.

Figure 1: Survey-based lighting consumption profile

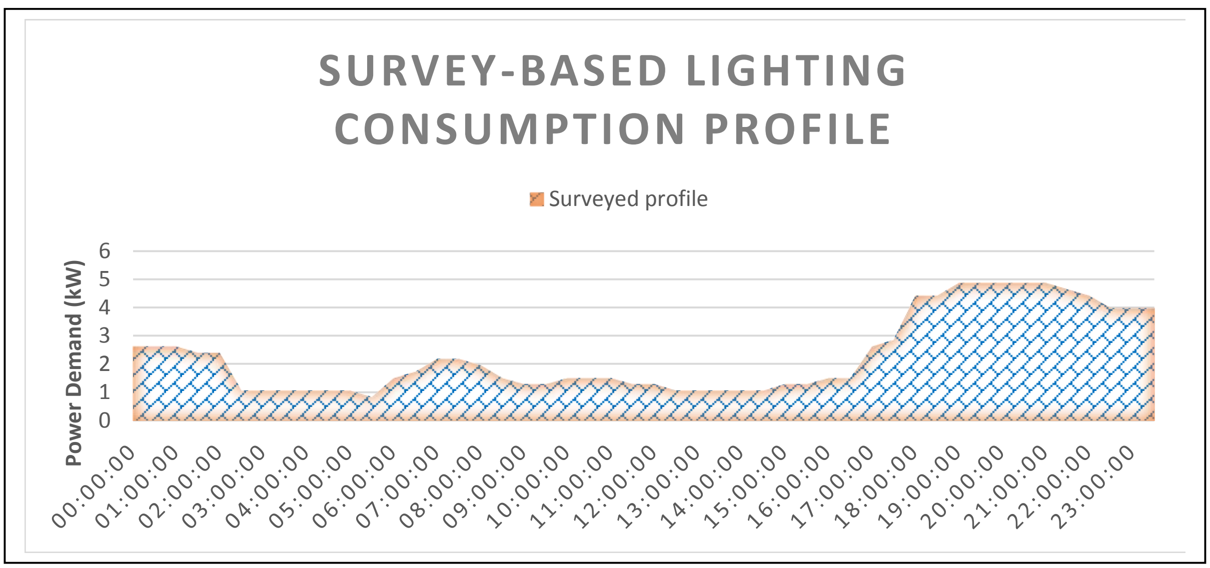

Figure 1 shows the peak consumption is around 4.8 kW and occurs between 18:00 and 21:00 whereas the lowest demand is around 0.8 kW and occurs between 05:00 and 06:00.

Data gathered through the loggers was recorded at five minute intervals for the duration of three days. The energy consumed for each hour of the three days was averaged to develop a 24 hour hourly profile. The daily average energy consumed was found to be 55.57 kW. The 24 hour hourly profile developed by averaging the hourly energy consumption of each day is presented in Figure 2.

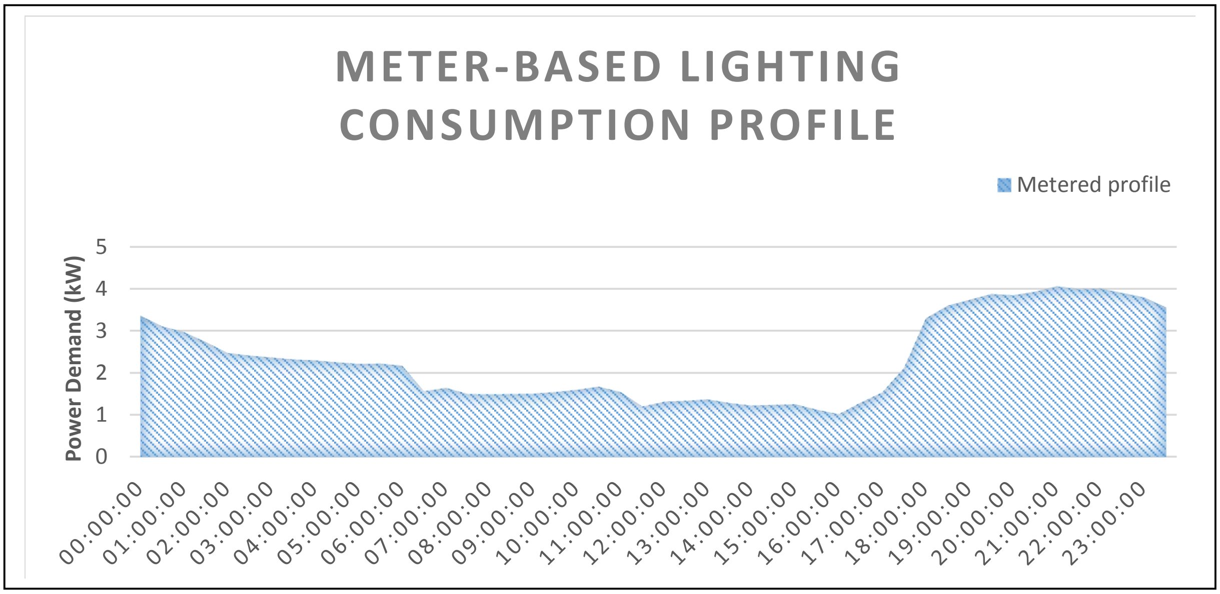

Figure 2: Meter-based lighting consumption profile

Figure 2 shows the peak consumption is around 4 kW and occurs between 20:00 and 22:00 whereas the lowest demand is around 1.2 kW and occurs between 15:00 and 16:00.

Meter results vs survey results

The purpose of conducting this test phase was to evaluate the quality of results obtained from the survey and to decide if these results should be used as they are or improved by conducting further investigations. From the results presented in the previous sections, the relative error on the daily energy consumption was found to be 0.16% and the errors on the peak power and lowest demand are respectively 20% and 33.3%. The difference between the two profiles can be observed in Figure 3 below.

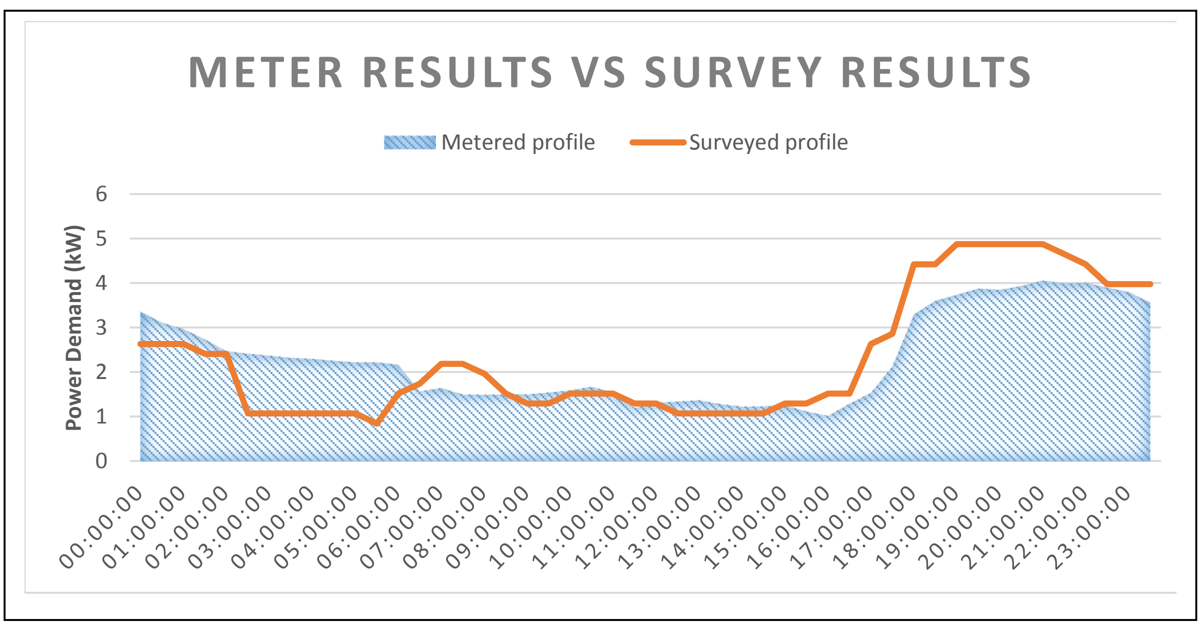

Figure 3. Profile comparison

Based on the project objectives, the budget available and accuracy required, the M&V practitioner can use these findings to decide if survey results are accurate enough for the project. For this particular project, the survey results may be suitable for calculating daily energy savings, but not very effective for computing peak demand reduction.

Conclusion

The purpose of this paper was to propose a practical method of assessing the accuracy of the data collected through interviews and site surveys for use in lighting retrofit projects. It was suggested that the results obtained from interviews and survey data can be compared to meter-based results. This comparison can assist M&V practitioners in evaluating the quality and accuracy of their results, especially in cases where human and sampling errors are difficult to assess. The case study illustrates how such a test phase can be designed and implemented in projects in the field. It would be interesting to see more similar case studies with a longer test phases and larger samples in order confirm the effectiveness of this approach.

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EU Energy Label on Vacuum Cleaners: evaluation and market changes

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Abstract

Energy Labels have already been established by the European Union for several years on some technical goods markets (TV; refrigerators and washing machines for example among major domestic appliances). As from September 1st 2014, the Small Domestic Appliances sector is affected for the first time with the implementation of an energy label on the vacuum cleaner market, with the aim of supporting the development of a less energy-consuming offer.

The market's changes related to the implementation of this energy label can easily be tracked through retail panel as well as the impact of these new rules on vacuum cleaners' sales and on energy consumption. Does the label have on impact an the market? How can sales be segmented according to the various criteria published on the label? Are more energy-efficient models sold, and will the label enable the reduction of European households' average electricity consumption?

Beyond reduced energy consumption, it can be crucial to evaluate the impact of the label on the vacuum cleaners' market in terms of upgrade offer and technical specification.

1. Introduction

1.1. Context and presentation of the label

As from September 1st 2014, an energy label is implemented on the vacuum cleaner market. [1] Manufacturers are bound to test the quality of their products according to some technical criteria and to publish results of these tests in the form of a label presenting grades and information related to the energy consumption of the model.

This label must then be systematically presented to consumers on a point of sale: on top of imposing new rules aiming at reducing average energy consumption when using a vacuum cleaner; the label should inform consumers and support their choice.

[1] European Commission Regulation (EU) No 666/2013 of 8 July 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for vacuum cleaners

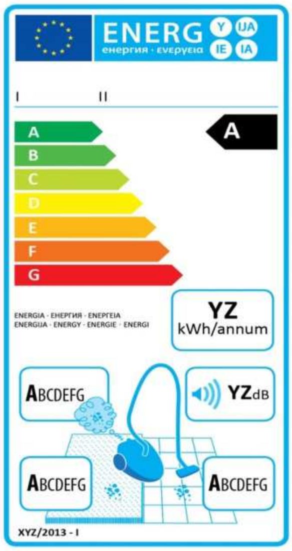


Figure 1: EU Energy Label on Vacuum Cleaners[2]

The energy label on vacuum cleaners includes following indicators:

- Energy efficiency class, from A to G, established according to the annual electricity consumption in kWh/year

Energy Efficiency Class	Annual energy consumption (AE) [kWh/year]
A	AE ≤ 28,0
B	28,0 < AE ≤ 34,0
C	34,0 < AE ≤ 40,0
D	40,0 < AE ≤ 46,0
E	46,0 < AE ≤ 52,0
F	52,0 < AE ≤ 58,0
G	AE > 58,0

Table 1: Energy Efficiency Class[3]

- Hard floor cleaning performance class, from A to G, established according to the dust pick-up rate on hard floors (tiles, linoleum, parquet floor, etc.)
- Carpet floor cleaning performance class, from A to G, established according to the dust pick-up rate on carpet floors, the dust cleaning capacity of a model varying on different floor types
- Dust re-emission class, from A to G, corresponding to the quality of filtration
- Sound level in decibels
- Annual average energy consumption in kWh/year

By including cleaning performance and filtration classes, the label emphasizes not only on energy

[2] Source CECED http://www.newenergylabel.com/uk/labelcontent/vacuum_cleaners

[3] European Commission Regulation (EU) No 665/2013 of 3 May 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of vacuum cleaners

savings, but also on the model's technical specifications. In this regard, the label also tends to encourage innovation.

Beyond the label, the European Commission regulation decrees a maximum power level of 1600 Watts, corresponding to an annual energy consumption of 62.0 kWh / year.

Finally, only some types of vacuum cleaners are affected by the energy label: cylinders, uprights and mains-operated vacuum cleaners.

1.2. Methodology

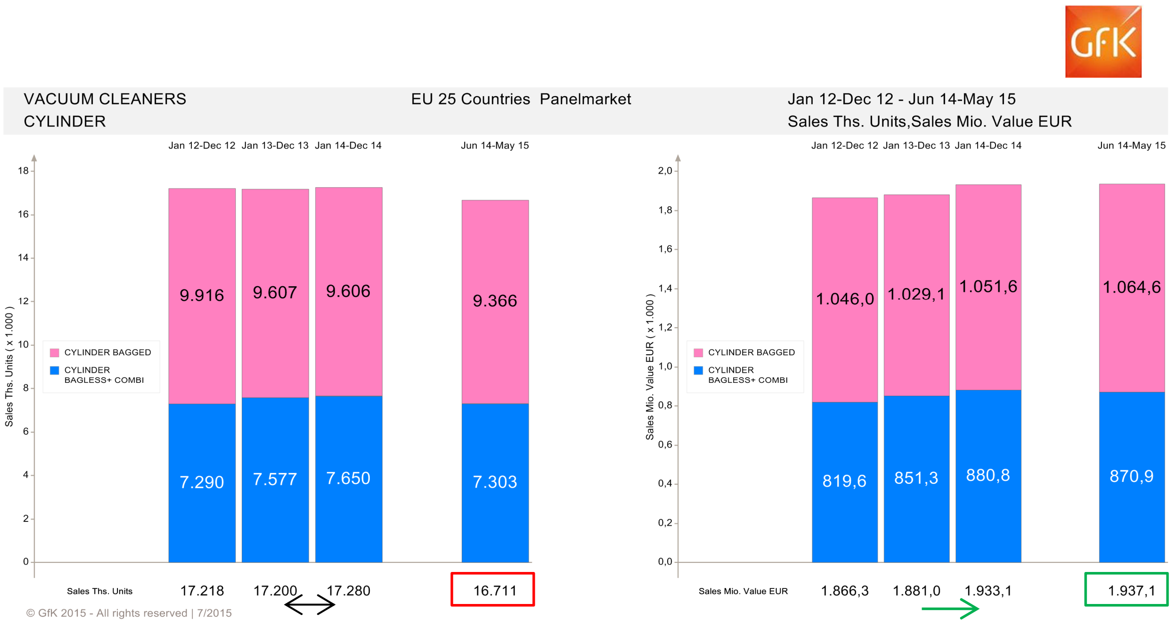
All figures regarding sales volumes mentioned below are based on GfK Retail & Technology retail panel. Over the 28 European Union member countries, GfK is auditing vacuum cleaners' sales in 25 countries[4] and measures sales-out volumes and average price on the model level. For every single vacuum cleaner sold, some technical features are identified, every indication of the energy label among them. Sales can be segmented according to the various criteria of the label, as a result. Manufacturers are responsible for the publication of the labels corresponding to their different vacuum cleaners models.

2. The European vacuum cleaner market is renewed with the implementation of the energy label

2.

2.1. The energy label is launched on a 17.3 million units market in 2014

Focusing on cylinders only, the main segment of vacuum cleaners and on which the energy label is applied, the market amounts to 17.3 million units and 1.9 billion euros in 2014 among the 25 European Union pre-cited countries. It is divided into two dust collection technologies: bagged cylinders, for which dust is vacuumed into a bag inside the device, and bagless cylinders, for which dust is directly collected in a container integrated to the appliance. Over the 3 past years, the cylinders market remained stable in volume but kept growing slightly in value. Looking at a 12 months market size with end-of-May 2015 data, sales volume are now declining while the market remains positive in value.



[4] AT, BE, CZ, DK, DE, EE, ES, FI, FR, GB, GR, HR, HU, IE, IT, NL, LT, LU, LV, PL, PT, RO, SE, SI, SK

Figure 2: source GfK Retail & Technology

2.2. The market is largely renewed with the implementation of the label

One of the objectives of the label was to drive the development of a low wattage offer. Indeed, a better suction quality does not necessarily imply a higher wattage power. Yet, the market was mostly built on high wattage levels before the launch of the label.

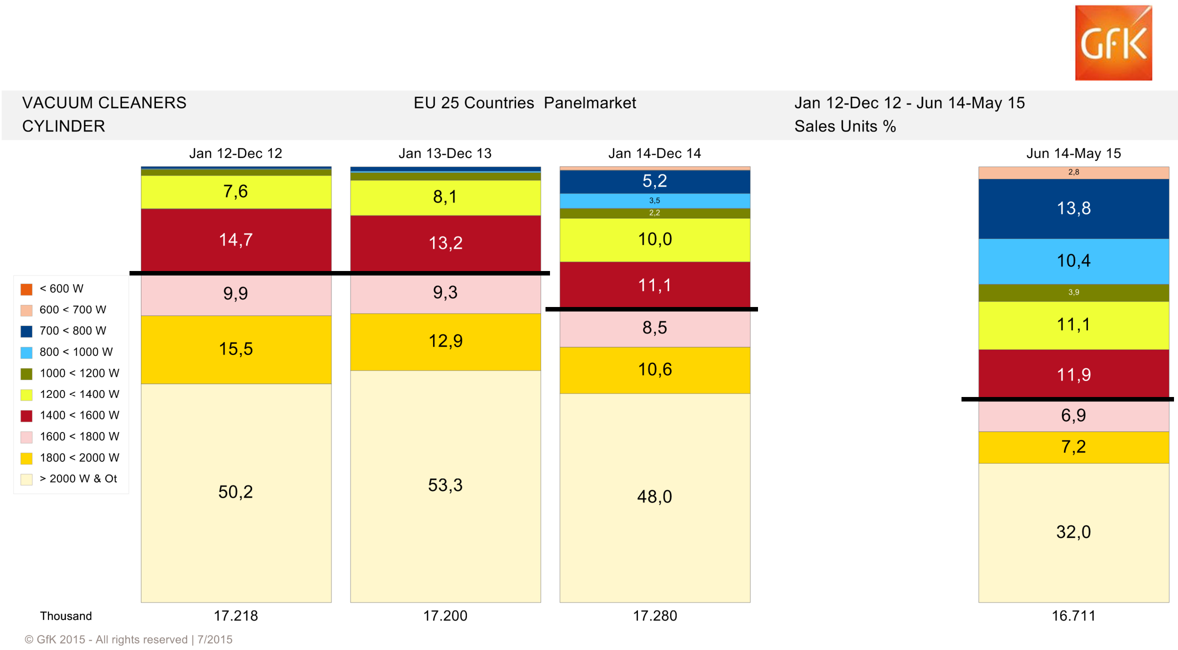


Figure 3: source GfK Retail & Technology

Since the regulation now decrees a maximum 1600 Watts power level, cylinders models accounting for more than ¾ of volume sales in 2013 did not fit new requirements and had to be replaced starting from September 1st 2014. As a consequence, the market was largely renewed: models launched after July 1st, 2014 account for 49% of the market's sales in December 2014, 76% in May 2015; models launched after July 1st, 2013 accounted for only 17% of sales in December 2013, 27% in May 2014.

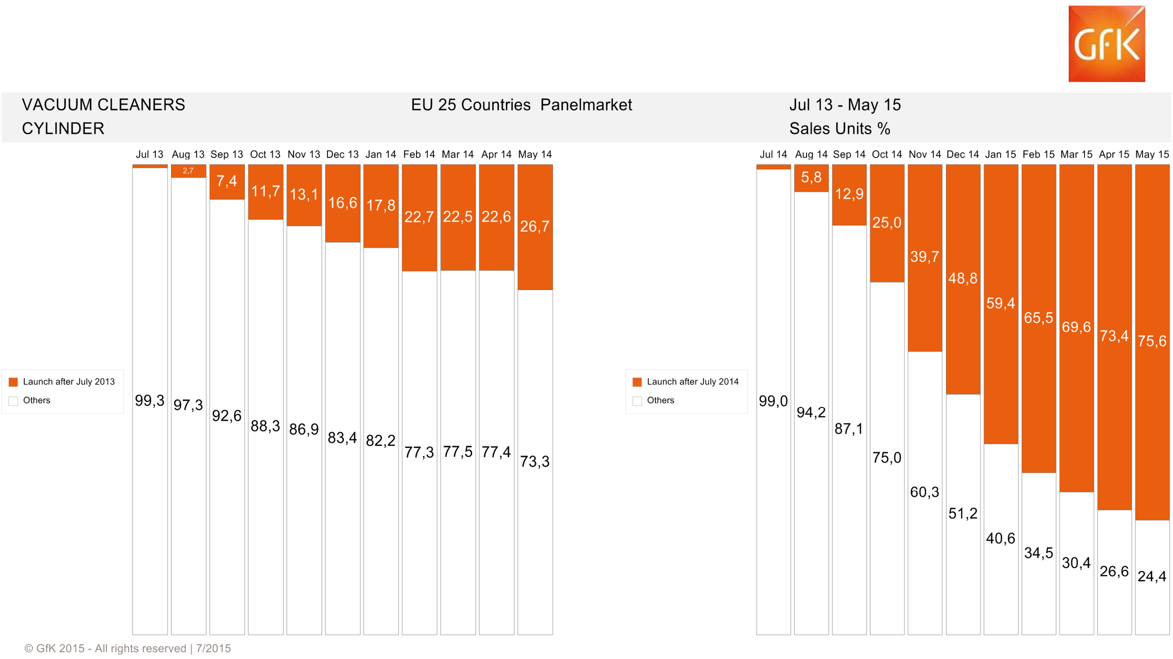


Figure 4: source GfK Retail & Technology

Now renewed with models with a power level below 1600 Watts, as requested by the energy label, the market is built on much more energy-efficient products. Models with a power level below 1600 Watts account for 62% of sales in December 2014, 81% in May 2015, compared to 24% in December 2013 or May 2014. Besides, the offer below 800 Watts, still very limited one year ago, now accounts for more than 30% of sales.

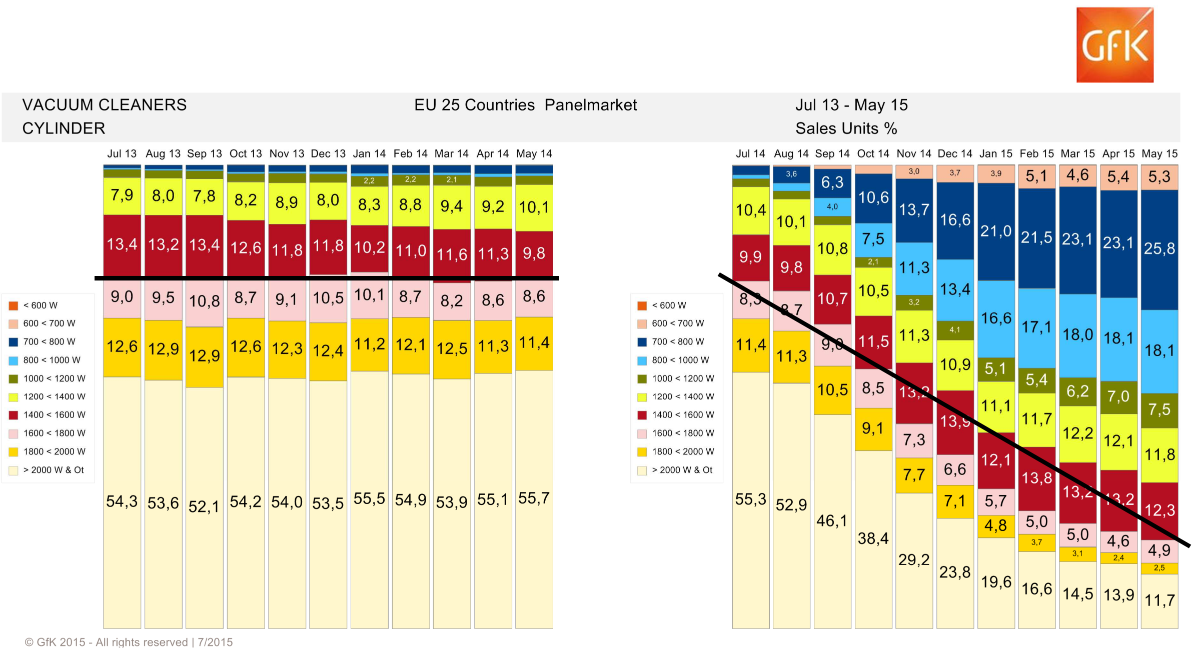


Figure 5: source GfK Retail & Technology

3. Segmentation of sales according to the label's criteria

The offer on cylinders is clearly more eco-efficient a few months only after the implementation of the label. The figures provided below are observed on renewed models only, launched after July 1st, 2014, with a label.

3.

3.1. Energy Efficiency

The general energy efficiency class is established according to the average annual energy consumption of a vacuum cleaner.

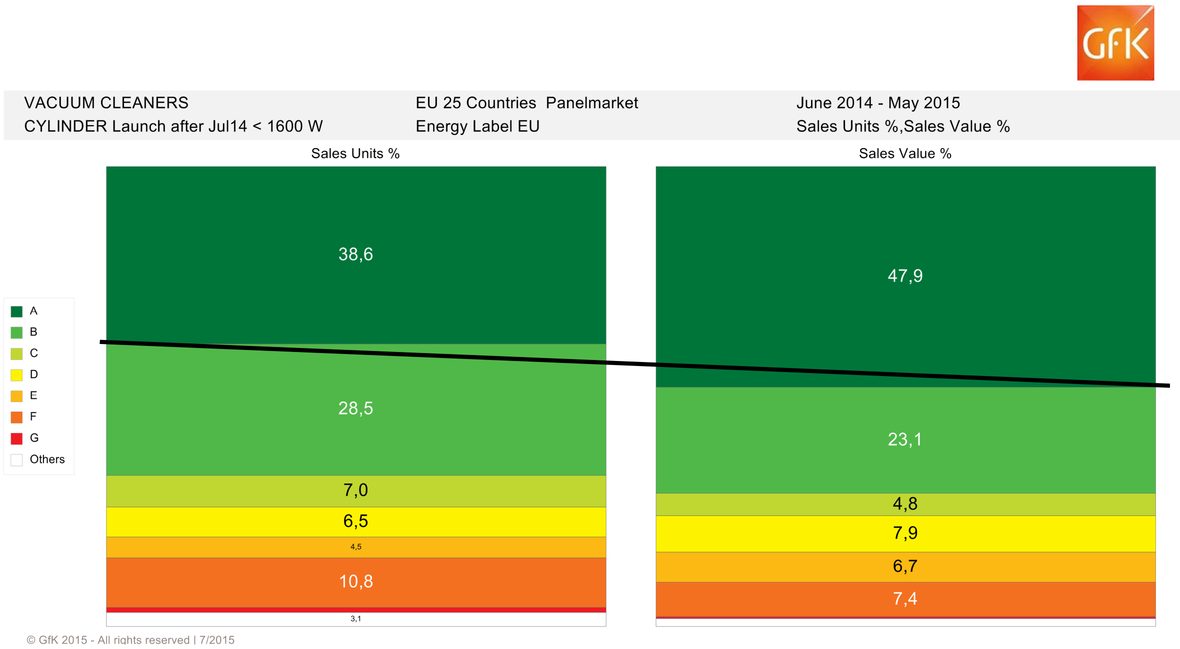


Figure 6: source GfK Retail & Technology

On a Moving Annual Total (MAT) basis with end-of-May 2015 data (12 months, June 2014 - May 2015), in the 25 pre-cited European Union countries, the energy efficiency A class is already the first class of the market, accounting for 39% of volume sales. It is a high-end offer: the average price of a A model is 154€ compared to 124€ on all renewed models. A models on the general energy efficiency class account for 48% of turnover.

3.2. Additional classes

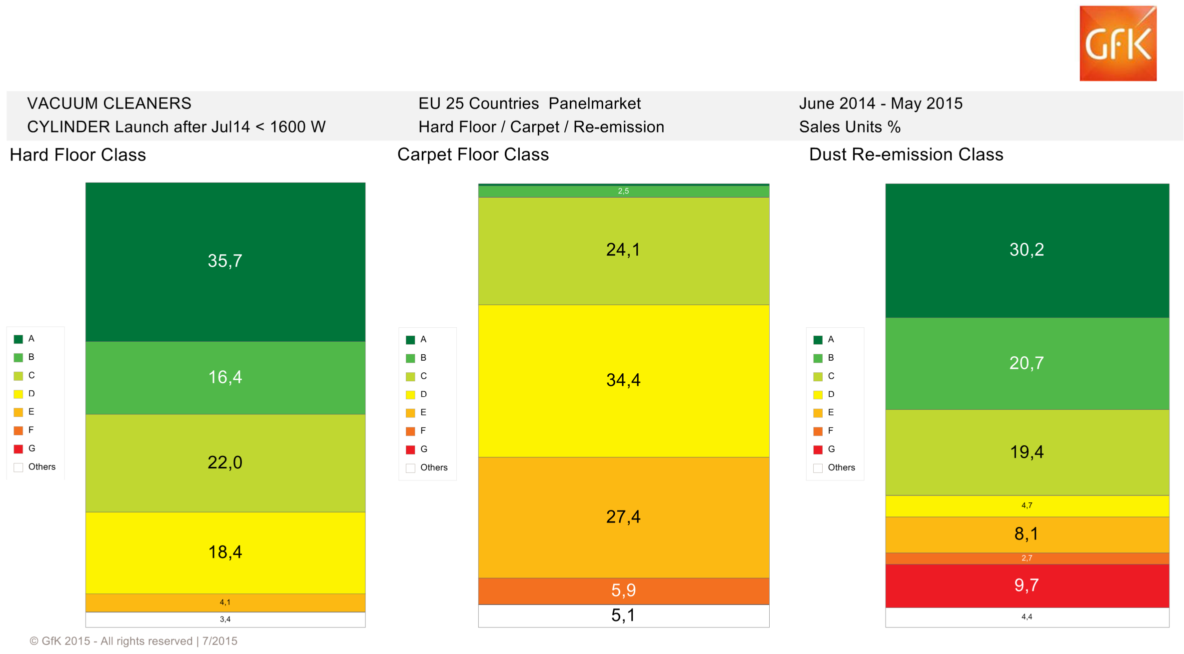


Figure 7: source GfK Retail & Technology

As for energy efficiency, the main class on hard floors cleaning performance is the A class; C and D classes remain however sizeable. Cleaning on carpet floor is unsurprisingly more demanding in terms of vacuuming capacities: the main class on this criterion of the label is D and the A and B offer on carpet floors cleaning performance is still very limited. Room for improvement is still high for manufacturers on this feature.

For dust re-emission, the most important classes are A, B and C. However, looking at the G class, under-performing models for this filtration function still account for 10% of sales, which is more as for other classes presented on the label. As a result, the cylinders offer remains much segmented in terms of quality of dust filtration.

3.3. Sound level

The label is presenting the sound level in decibels of the model. According to manufacturers, 3 decibels less for one model compared to another correspond to a twice as low perceived noise[5]. A vacuum Cleaner can be regarded as silent with a noise level below 75 dB (or even 70 dB).

[5] Source Gifam: http://www.choixresponsable.com/guide-achat-aspirateur/

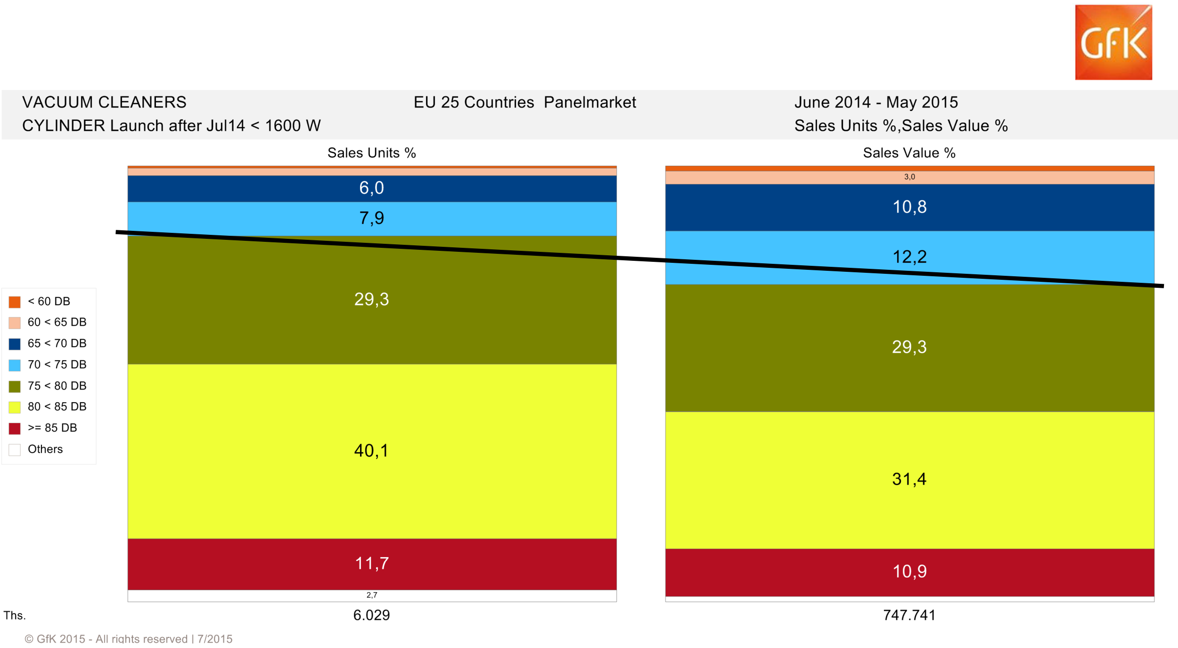


Figure 8: source GfK Retail & Technology

Over the renewed cylinders on which the label can be applied, appliances with a sound level below 75 dB account for 16% of volume sales. As a result, there is still a strong potential for the development of silent vacuum cleaners. Since the implementation of the label, first products below 60 dB have been sold. Besides, silent models bring added value to the market: 16% of volumes sales, accounting for 27% of turnover.

4. Evaluation of the label's impact on energy consumption and on the market

4.

4.1. Energy savings

The implementation of the energy label on vacuum cleaners is part of the larger frame of European Commission Ecodesign and Energy Labelling directives, related to the 2020 Objective of the 20% reduction of greenhouse gas emissions compared to 1990 and a 20% improvement of energy efficiency over the same period[6].

According to the European Commission, the average power level of vacuum cleaners rose from 1275 Watts in 1190 up to 1500 Watts in 2005 and could have reached 2300 in 2020 without the implementation of the label. Similarly, the average annual electricity consumption of one vacuum cleaner, used one hour per week, which amounted to 60 kWh / year in 1990, could have doubled and reached 120 kWh / year in 2020[7].

The energy label now shows the level of average annual electricity consumption in kWh / year of the model, under the basis of 50 cleaning actions per year, an 87 m² average household surface and 4

[6] Source European Commission : http://ec.europa.eu/europe2020/europe-2020-in-a-nutshell/targets/index_en.htm
[7] Source European Commission – Impact Assessment accompanying the Commission Regulation Directive 2009/125/EC and the Commission delegated Regulation supplementing Directive 2010/30/EU: http://ec.europa.eu/smart-regulation/impact/ia_carried_out/docs/ia_2013/swd_2013_0241_en.pdf

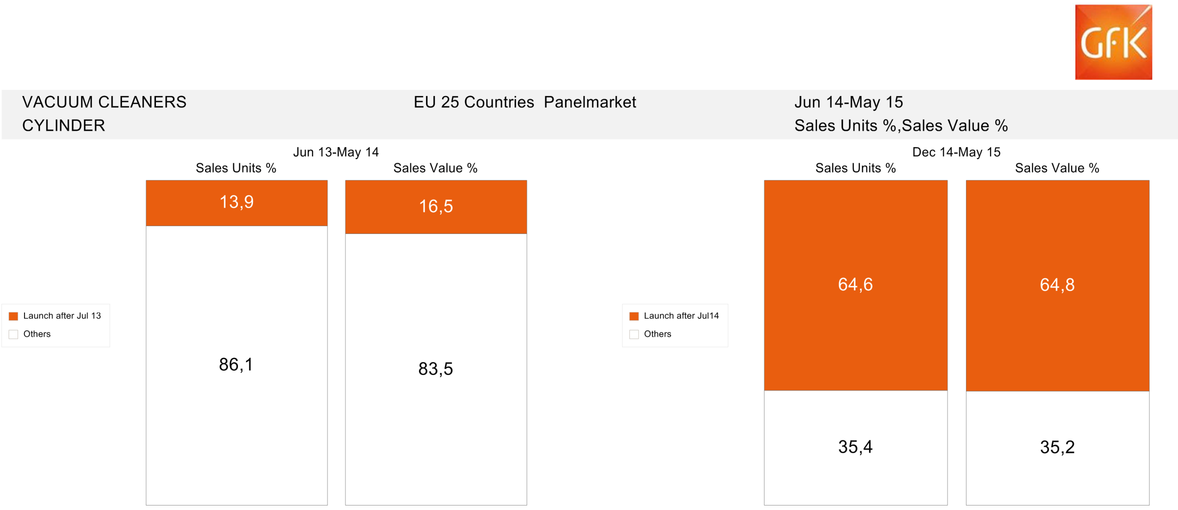
strokes of the vacuum cleaner over each point on the floor for one use[8]. Thanks to the tracking of all indications on the label, for each sold product, the average energy consumption of sold vacuum cleaners in Europe can be evaluated through GfK Retail and Technology retail panel. On a MAT basis with end-of-May 2015 data (June 2014 – May 2015), the average maximum power level and the average annual energy consumption of renewed cylinders amount to:

- ⇨ Average maximum power level: **917 Watts**
- ⇨ Average annual electricity consumption: **34,5 kWh / year**

As a result, the objective of energy savings on the vacuum cleaner market seems to be reached since the launch of the energy label.

4.2. The market is going upscale thanks to the label

With the energy label, consumers are now informed on appliances' functionalities in terms of energy savings, cleaning performance, dust re-emission and sound level. What is the impact on the cylinders European market?



	Jun 13-May 14
Total	110
Launch after Jul 13	130
Others	107

	Jun 14-May 15
Total	116
Launch after Jul14	123
Others	111

Figure 9: source GfK Retail & Technology

The implementation of the label has clearly supported upscale sales on the cylinders market over the last 12 months (June 2014 – May 2015). The average price of a cylinder amounts to 116€ and rose by +5% (+6 EUR). Sales have declined during this period in volume (-3% in volume); the label had no impact on sales as a result. However, the market's turnover grew by +2%; the label has definitely brought added value to the market.

[8] Source European Commission delegated Regulation (EU) No 665/2013 of 3 May 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of vacuum cleaners

4.3. Revision of the energy label

There will be two stages for the reduction of energy consumption with the label. As from September 1st 2014, a maximum 1600 Watts power level is requested for vacuum cleaners, corresponding to a maximum 62.0 kWh / year average annual energy consumption; as from September 1st 2017, this upper limit will be reduced down to 900 Watts, corresponding to an average annual energy consumption of 43.0 KWh / year. The conditions for the attribution of the different classes will be updated as a result, with the creation of new A+++, A++ and A+ classes, as detailed in the table 2. The sound level for vacuum cleaners will also be limited to 80 decibels.

Energy Efficiency Class	Annual energy consumption (AE) [kWh/year]
A+++	AE ≤ 10,0
A++	10,0 < AE ≤ 16,0
A+	16,0 < AE ≤ 22,0
A	22,0 < AE ≤ 28,0
B	28,0 < AE ≤ 34,0
C	34,0 < AE ≤ 40,0
D	AE > 40,0

Table 2: Energy Efficiency Class[9]

Beyond the revision of the label, the perimeter of application of this label may also have an influence on energy savings. Cylinders do remain the biggest segment on vacuum cleaners, but they tend to lose shares in front of battery-operated appliances such as rechargeable handstick vacuum cleaners.

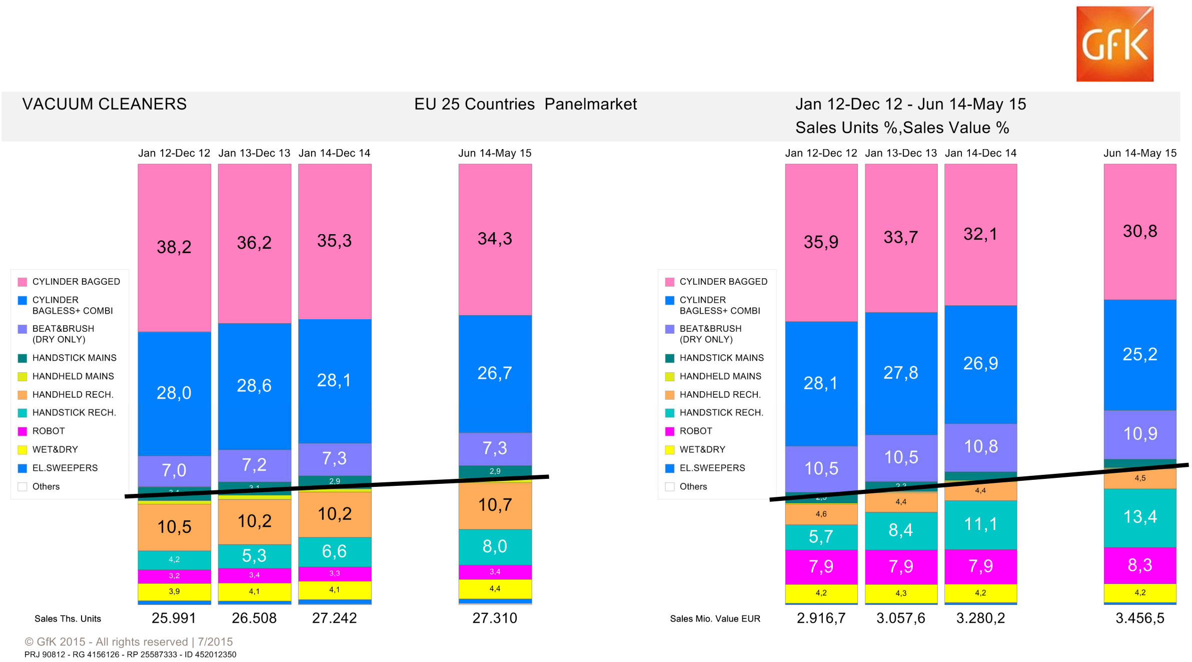


Figure 10: source GfK Retail & Technology

[9] European Commission Regulation (EU) No 665/2013 of 3 May 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of vacuum cleaners

So far, the label can be applied on cylinders, uprights and mains-operated handstick vacuum cleaners only. Considerable advances are being reached on the energy efficiency of these products; this offer is however losing shares compared to vacuum cleaners outside the perimeter of application of the label.

5. Conclusion

The Energy Label has been applied on cylinders, the biggest segment of vacuum cleaners, since September 1st, 2014. Models sold have been largely renewed in order to fit new requirements from the European regulation.

Among pre-cited EU countries, the energy efficiency A class already accounts for close to 40% of volume sales and 50% of value sales. The level of energy consumed through the use of cylinders is reduced, with an average maximum power level of 917 Watts and an average annual electricity consumption of 34,5 kWh / year.

Consumers are also informed on cleaning performance, quality of dust filtration and sound level. The introduction of the Energy Label does not have any impact on volume sales. However, consumers seem to be willing to invest more; with a growing average price on cylinders, the label is bringing added-value to the market.

Cylinders are consuming less, and new requirements will be established with the update of the Energy Label in 2017. Over the total vacuum cleaners market however, cylinders are losing shares in front of battery-operated devices which do not belong to the scope of the energy label.

Monitoring the washing machines market in Europe

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Abstract

French Energy Agency ADEME and WWF Switzerland have set up a project with Topten to track trends on the white goods market in Europe and selected countries. This paper presents the results from the analysis of washing machines sales data, purchased from market research company GfK, in Europe, France and Portugal. The data covers the period 2004 to 2014 and analyses trends in energy efficiency, energy consumption, size and price of washing machines.

Results show that the European market moved faster than energy efficiency policies during the 10-year period observed. For example, already in 2004 more than 80% of the sales were in the official top class A. Before the Energy Label was amended with classes A+, A++ and A+++ in 2010, many of the models available were already marketed as A+, A-10% or A-20% In 2014, A+++ already accounted for 43% of the sales.

Our analysis shows that current Ecodesign and Energy Label policies for washing machines could have been set at a higher level had there been sales data available. Indeed, systematic market monitoring (i.e. the tracking and analysis of sales data) can help set minimum energy performance standards (MEPS) and energy labels that are meaningful and truly steer markets towards more energy-efficient products. The cost of tracking and analysing market data would be more than offset by the increased energy and economic savings associated to better fine-tuned policies.

Background

Minimum energy performance standards (MEPS) and Energy Labels support market transformation towards higher energy efficiency. In order to reach maximum impact, these instruments need to be well designed: MEPS should be stringent enough to create a market ‘push’ effect. Energy Labels should cover the entire market and offer challenging label classes yet to be reached in order to ‘pull’ the market. Market analysis from Switzerland has shown that where most of the products are in the Energy Label’s top class, innovation almost completely stops for many years (e.g. example dishwashers 2004 – 2011 or ovens 2004 - 2013 in [1]). When the Energy Label is revised to offer new, empty top classes yet to be reached, the market starts to move again (e.g. washing machines in 2008 (when Switzerland introduced the A+ class) and 2012, and dishwashers in 2012, in [1]). Where the Energy Label keeps offering an incentive for further efficiency innovation, the market can constantly improve (e.g. refrigerators and freezers 2004 – 2013 in [1]).

In order to design effective policy measures and revising them before innovation comes to a stop, it is crucial that policy makers have a clear picture of the market. Understanding the development in e.g. sales, size, energy efficiency, energy consumption and price allows policy makers to design MEPS and Energy Labels that are effective for several years. It would also allow evaluating the policies’ effectiveness and to revise them in time [2]. As long as an Energy Label covers the entire market and several classes are ‘populated’ with models, the Label provides a perfect tool for easy market analyses. If sales data is available over a long period, stock and energy consumption models can be derived [2].

Most important economies (e.g. Australia and New Zealand, Brazil, Canada, China, India, the USA) have set-up mandatory product registration systems, resulting in a product database containing specifications of all models marketed [3]. In most cases, these databases are publicly accessible and can be used by the government and stakeholders to support the policy making process. Some countries combine such model information with sales data to track market changes according to sales weigh: Australia additionally purchases sales data on model level from a professional market research company to evaluate and plan its policies, while in New Zealand manufacturers and suppliers are required to provide aggregated sales data to the government annually [3].

Europe is lagging behind as it does not monitor markets of energy-using products (except for cars [3] which indicates that it is possible in Europe), neither with a product registration system on model basis, nor with sales data. Instead, whenever market data is needed for a preparatory study or impact assessment, available data is collected in a time-consuming process by consultants. Usually this data is provided by industry and is neither complete nor up-to-date, and cannot be compared over time and between countries.

As a consequence of this lack of sound market data, product policy measures have been designed not ambitiously enough and energy savings have been missed. Examples are the ban of refrigerators classes B and C in 2010 (only 4% B and 0% C was left on the market in 2009, [11]), or the Energy Labels for washing machines and dishwashers, with the new top class A+++ already populated after a short time.

Objectives

The aim of this paper is to demonstrate the value of systematic market monitoring based on sound sales data for washing machines. It complements other market monitoring reports such as the ones on TVs [5], refrigerators [6], tumble driers [7] and the ones on household appliances from Switzerland [1]. At the same time the data presented here supports the on-going revision of the washing machines Ecodesign and Energy Labelling regulations [8, 9]. With national sales data from France and Portugal for the 2004-2014 period, these countries can learn how national and European energy efficiency policies and campaigns have impacted the appliances markets. This data also provides a solid basis for these countries' input into the Energy Label and Ecodesign revision process, as well as for defining national strategies and campaigns to support the market transformation towards higher energy efficiency.

Washing machines: Regulatory context

The first A to G EU Energy Label for washing machines was introduced in 1995 [10]. The Label was based on a kWh/kg capacity efficiency definition, with 0.19 kWh/kg being the threshold of class A. The energy consumption was defined based on a full load test at 60°C. In 2010, the Energy Label was amended with classes A+ to A+++ [9]. At the same time, the efficiency definition was changed: the Label classes are now based on an Energy Efficiency Index (EEI), the calculation of which is based on annual energy consumption including low power modes and does also consider tests at 40°C and with part load, additionally to the full load 60°C programme. The measurement standard was amended to include these wash cycles, but also additional features were changed (e.g. different detergent and type of soil). As a result, declarations before and after 2011 have to be compared very cautiously. The new Label was compulsory from December 2011, while both Energy Label versions could be used in the period from December 2010.

From the same date, the Ecodesign regulation applied, banning washing machine models not reaching efficiency class A from the market [8]. Other requirements concerned washing efficiency (min. former class A) and maximum water consumption. In December 2013 this MEPS level was lifted to class A+ efficiency. Since then, all washing machine models must offer a 20°C programme.

Before the new Label officially introduced the 'plus'-classes, manufacturers had already marketed their machines that were exceeding class A efficiency as 'A-10%' or 'A-20%'. Based on a voluntary agreement between the Commission and CECED, some manufacturers officially labelled these products as 'A+' before December 2010.

The Ecodesign and Energy Labelling regulations are both being revised at the moment. A preparatory study has been launched which will make suggestions for new Label and Ecodesign requirements[1]. New measures are expected to be implemented in 2016.

Data and Methodology

Thanks to funds from ADEME[2] (Agence de l'Environnement et de la Maîtrise de l'Energie), the Topten study team could purchase sales data of washing machines for the EU, France and Portugal from

[1] http://susproc.jrc.ec.europa.eu/Washing_machines_and_washer_dryers/index.html

GfK, a professional market analysis company present around the world[3]. In Europe, GfK covers around 90% of the refrigerator market, and all 28 Member States.. Sales data plus many product characteristics are obtained from retailers.

GfK provided washing machines sales data including information regarding energy classes and average size, energy and water consumption and price, covering years 2004 to 2014. This data was obtained for France, Portugal, as well as for an aggregation of 21 EU Member States[4]. All information about specifications is according to the declaration on the Energy Label, with a few exceptions that are explained below (A+ and A++ classes and energy and water consumption before 2011). Sales data from Switzerland [1] is published annually and is also used here for comparison reasons.

Similar data was purchased for refrigerators and tumble driers. This is also presented at the EEDAL conference 2015 (papers No. 50 [6] and 58 [7]). Further results about washing machines, refrigerators and tumble driers will also be published on topten.eu [11] in May 2015.

Results and Interpretation

Sales numbers increased from 13.5 million to 15.1 million units from 2004 to 2007 in the EU-21 considered here, then fluctuated around 15 million units per year. In 2014, 15.2 million washing machine units were sold. Sales in France show a similar pattern, stabilizing after 2010. In 2014, 2.38 million units were sold in France. In Portugal sales numbers climbed until 2011, then declined in 2011 and 2012. In 2014 sales were back at the 2009 level, at 284'000 units. (See also [11].)

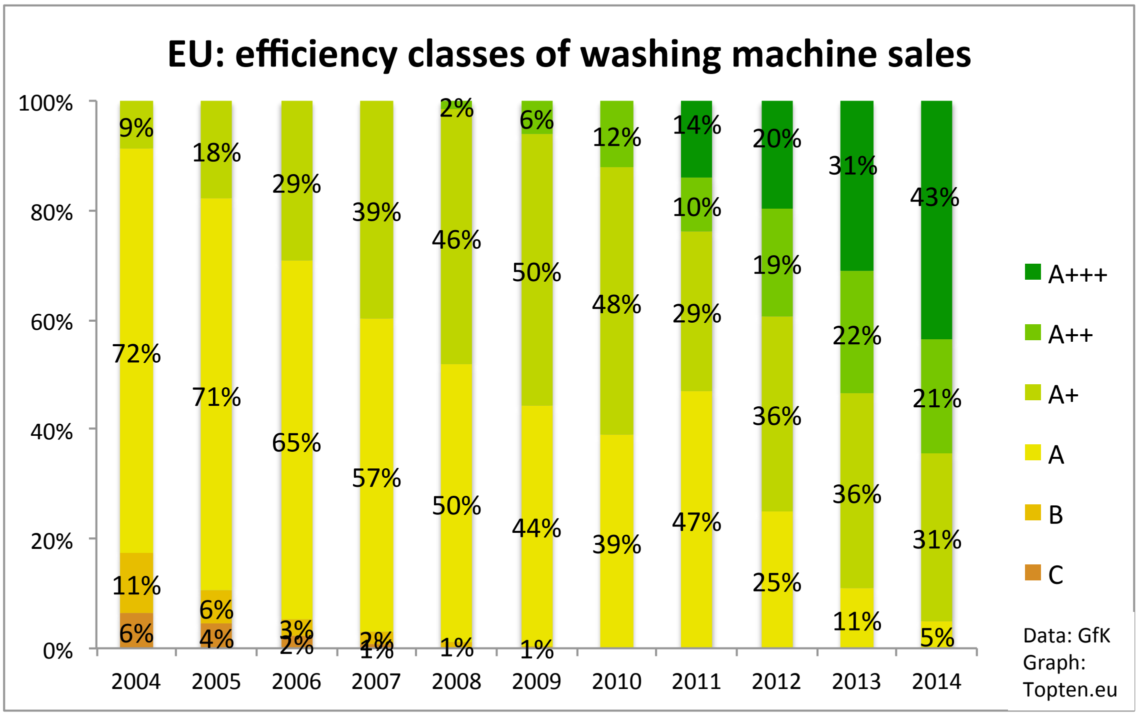

Fig. 1: The most sold efficiency class has improved from A to A+++ in ten years

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[2] www.ademe.fr/

[3] www.gfk.com

[4] EU-28 without Bulgaria, Luxembourg, Estonia, Latvia, Lithuania, Malta and Cyprus.

Classes A+, A++ and A+++ were only 'official' starting in 2011: before 2011, GfK categorized as A+ whatever was declared as 'A-10%' (or A+), and 'A-20%' as A++. Sales share of these classes before 2011 has to be read with caution.

The efficiency development of washing machines happened much faster than expected by the Commission. Already in 2004 the Energy Label was out-dated, with more than 80% of the sales in the official top class A. By 2010, when in December the new Energy Labelling regulation entered into force, 60% of the sales exceeded the class A threshold by 10% or more. There is an increase in class A sales share from 2010 to 2011 – most likely due to the change of Label classification and test measurements that happened at the same time. Still, already 14% of the sales were in the new top class A+++ in 2011, the transition year of the new Label. Tier 1 of the Ecodesign regulation, banning class B and less efficient from December 2011, was obsolete from its entry into force. These classes had been virtually gone from the market several years earlier. Tier 2, banning class A from December 2013, was of minor effect – 11% of the sales still occurred in this class in 2013. In 2014, 43% of the sales across the EU were in the top class A+++. Three years after the new Label became compulsory, close to half of the sold washing machines were in the top class.

Figures 2 and 3 show that popularity of the efficiency classes can vary considerably on national markets. The French market seems to have been less efficient than the EU average since 2005. In 2014, A++ had a higher sales share in France than in Europe (25% compared to 21%), but also A+ (39% vs 31%), and A+++ made up for only 31% of French sales compared to 43% in Europe. In Portugal on the other hand the sales share of A+++ is already close to 50%, while yet in 2004 the sold washing machines were clearly less efficient than in the average of the EU. The high efficiency of the Portuguese washing machines market might be linked to the popularity of large washing machines [11] (large machines tend to reach higher efficiency levels, see fig. 8). Even higher A+++ sales shares can be found on the Swiss graph in [1]: 56% in 2012 and 61% in 2013.

These results imply that classes A+ to A+++ were introduced too late, and that class thresholds were not defined ambitiously and wide enough. Indeed with 13% (A+) and 12% (A++, A+++) the relative efficiency improvements between the classes are smaller than in other Labels (e.g. refrigerators & freezers: A++ 21%, A+++ 33%; TVs: A+ 23%, A++ 30%), and actually only slightly larger than the measurement tolerance of 10% (on energy consumption). The current revision of the Label is overdue. A new Label will not be in place before 2017, until then manufacturers have no possibility to market energy efficient innovations. However, these are already on the market: the best washing machine model is exceeding the A+++ threshold by more than 50% (V-Zug Adora SLQ-WP with integrated heat pump; EEI= 22.8, 8kg. Source: www.topten.eu).

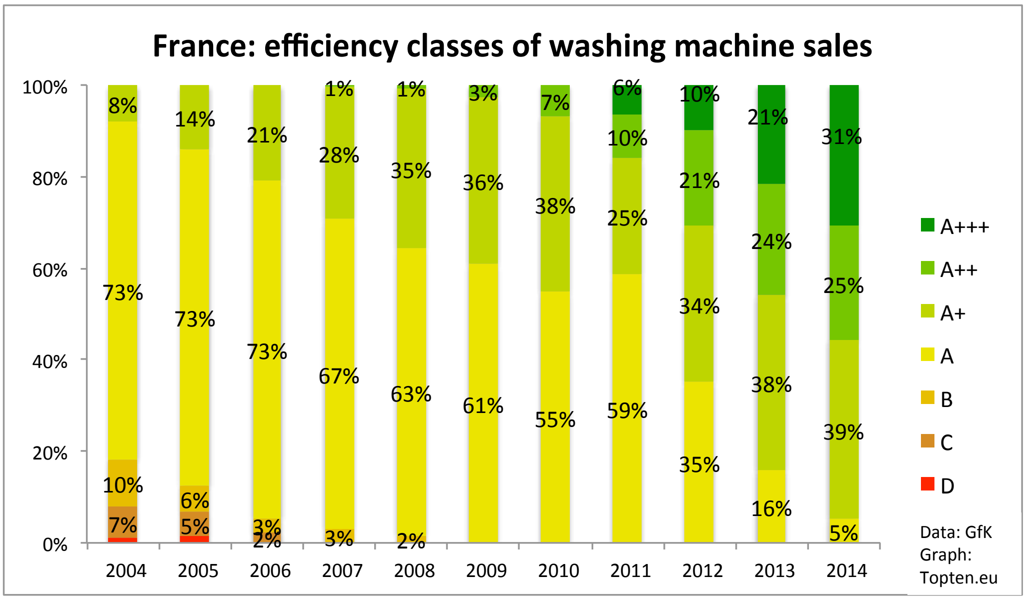

Fig. 2: In France, A+ was the most important class regarding sales in 2014

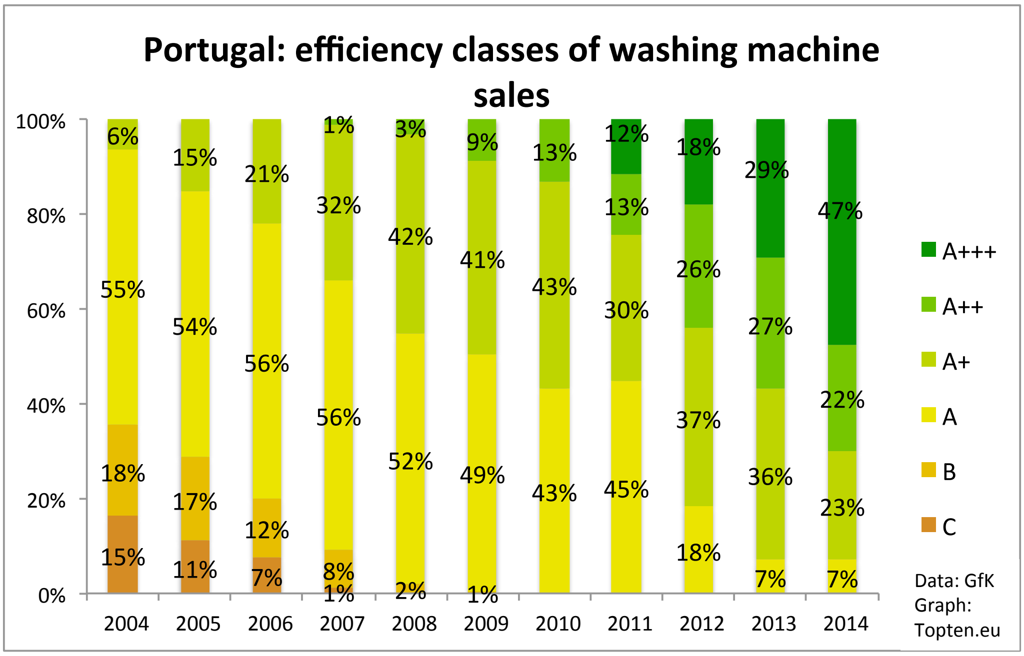

Fig. 3: In Portugal, A+++ already accounted for 47% of the sales in 2014

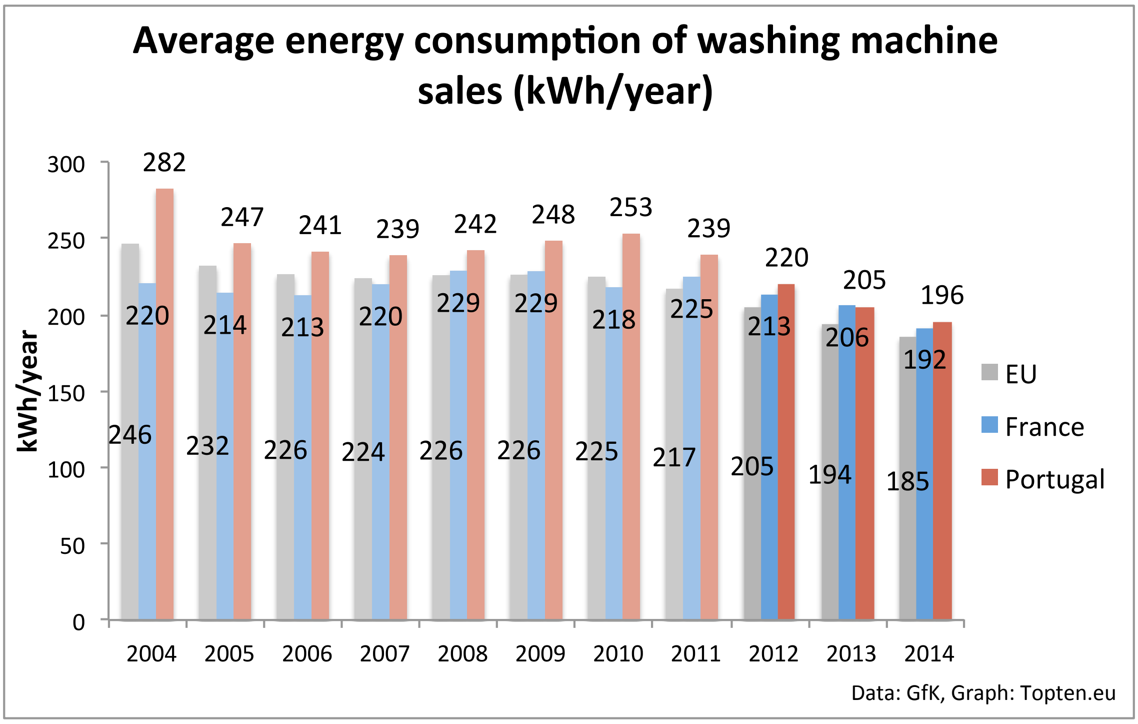

Fig. 4: Average annual energy consumption of sold washing machines started to decline after 2010.

Before 2011/12 the energy consumption was declared in kWh/cycle. These values have been multiplied by 220 by GfK. This is the number of annual cycles assumed for the declaration on the 2010 Energy Label which applied from December 2011. Since the new declaration also includes part load, 40°C cycles and low-power modes consumption, the values are not 100% comparable. While the exact values have to be read with caution, this chart can show trends before 2011 and after.

After a reduction from 2004 - 2006, average annual energy consumption of the sold washing machines remained stable at around 226 kWh/year in the EU. Only in 2011, with the introduction of the new Label, it started to go down. In France and Portugal, average energy consumption even increased between 2006 and 2009 / 2007 and 2010, respectively, before also decreasing. Since no change in declaration occurred, the trend to larger machines (shown in [11]) must have outweighed increasing efficiency in this period. In 2014, average annual energy consumption of the sold washing machines was 185 kWh per year in the EU-21, 192 kWh/year in France and 196 kWh/year in Portugal.

The reduction in declared and calculated energy consumption between 2004 and 2014 is 25% at EU level, 30% in Portugal and 13% in France. This is comparable with the reduction that happened in refrigerators, as shown in [6]. In the case of refrigerators the energy declaration however remained the same, while for washing machines the real reduction is not so clear because of the changing declarations: the new declaration is no longer only based on full load 60°C washing cycles (three out of seven), but includes also 60°C half load and 40°C half load cycles (each two out of seven), and the measurement standard changed. These changes mean that there is now an incentive for manufacturers to also optimise the energy consumption of the 40°C and part-load pogrammes. However part of the lower energy consumption after 2011 might be due to the inclusion of these less energy consuming programmes – while on the other hand newly also low-power modes were included (which can represent up to 12 kWh/year [12]). Own calculations, based on the values recommended by the Commission in 2009 for transitioning between the old and new methods [13] and values published on www.topten.eu[5], imply that around 10% of the reduction in energy consumption might have occurred due to different methods. Still, the average declared energy consumption has continuously been reduced since 2011 - despite a strong trend to larger washing machines (fig. 5). Clearly the tested programmes have indeed been optimized regarding energy efficiency.

It is surprising that in Portugal, where most energy efficient washing machines were sold, the average energy consumption is highest. An explanation can be found in the comparable large capacities that Portuguese buy: while across the EU in 2014 still 41% were 6kg and smaller machines (fig. 5), in Portugal only 20% were small (we use the term‘small’ here for convenience reasons, even though 6 or even 5kg machines were the standard ten years ago), 44% were declared as 7kg machines and 28% as 8kg |11]. This situation shows that larger capacity can cancel or even outweight the savings of better-rated machines – at least for a usage according to the Energy Label.

Effective energy consumption of course depends on the usage of the machines. According to a product expert[6], Portuguese use their wasing machine often (more often than dishwashers) and wash rather small loads. According to the expert, Portuguese consumers do not choose large washing machines because they wash large loads, but because nearly no small machines are offered on the market.

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[5] The Commission recommended to assume that the energy consumption of a 60°C half load programme is 0.8 times that of a 60°C full load, and the consumption of a 40°C half load 0.64 that of a 60°C full load programme. Furthermore, 12.5 kWh per year were added for the Standby and Off modes. Data from Topten.eu shows that these assumption are still fairly correct (in September 2014, just after the product lists were updated), but variations are large. The consumption by low power modes has not been compared.

[6] Oral information from Laura Carvalho, Quercus / Topten Portugal (www.topten.pt/) in March 2015

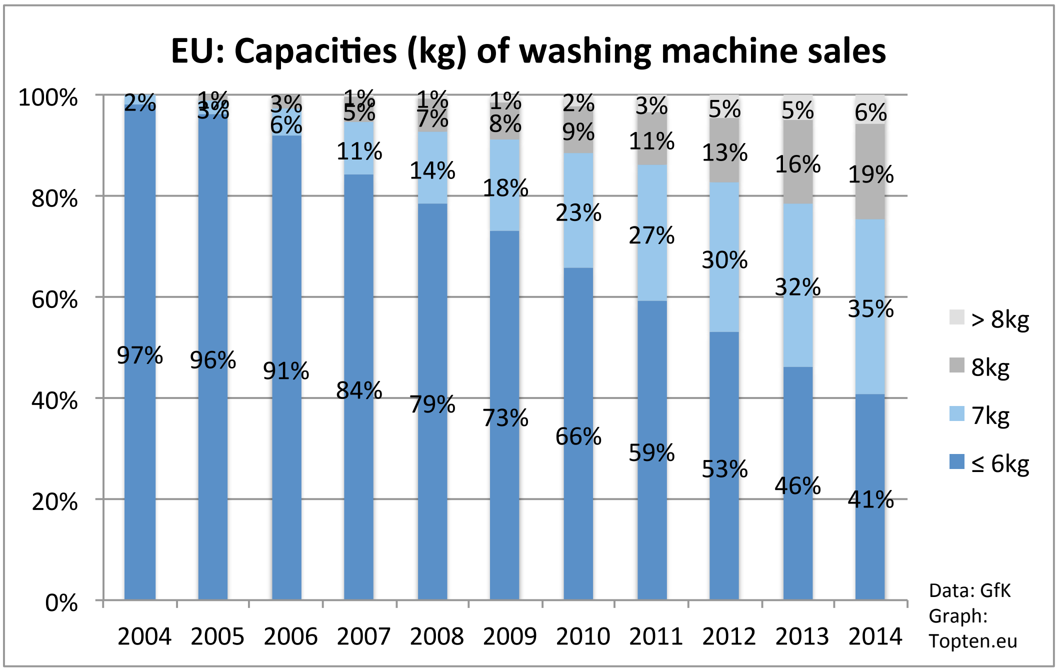

Fig. 5: There is a strong trend to larger capacities.

Ten years ago nearly all washing machines were for 6 kg of laundry and less, then the strong trend to larger capacities started. In 2014, more than half of all washing machines sold were designed for washing 7 kg laundry and more. It seems that the trend to large washing machines is rather coming from the changed market offer than from consumer demand. It is questionable if washing habits are changing so suddenly to washing larger loads, especially since the average household size is declining (Eurostat). The Energy Label might be at least partly responsible, since it was easier for large machines to reach good efficiency levels. With the new EEI system and the inclusion of part load washing the effect is less direct than it was in the old Label, but the trend has been continuing. Even if they are A+++, oversized washing machines do not contribute to energy saving. Instead, energy and water will be wasted if most wash cycles run with low part loads (e.g. 2-3kg in 8kg machines).

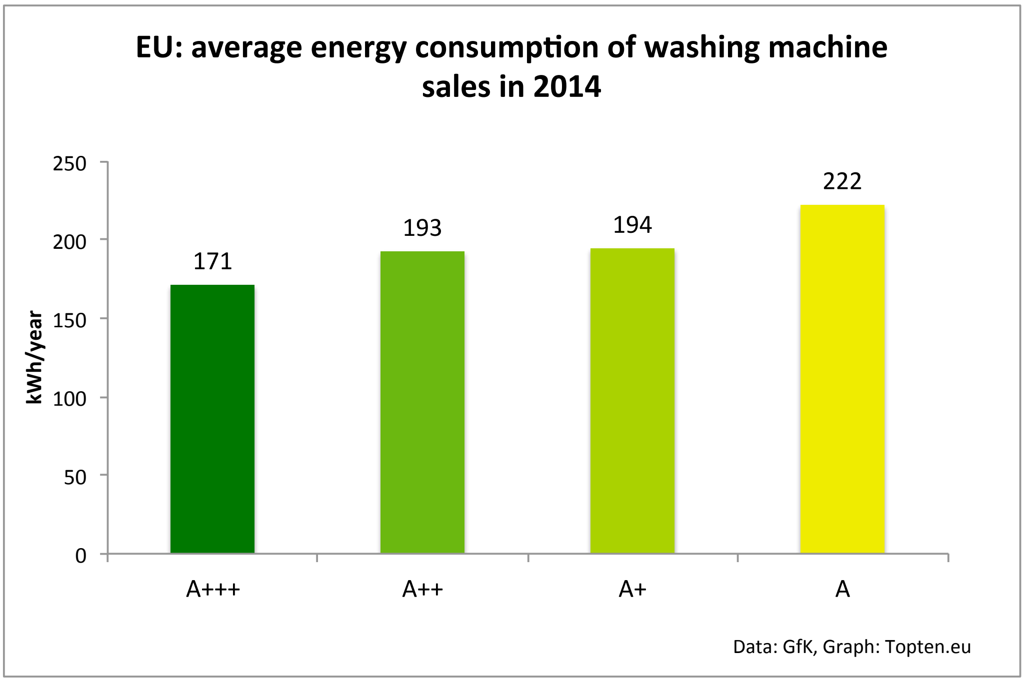

Fig. 7: Energy consumption differences between efficiency classes are not so large

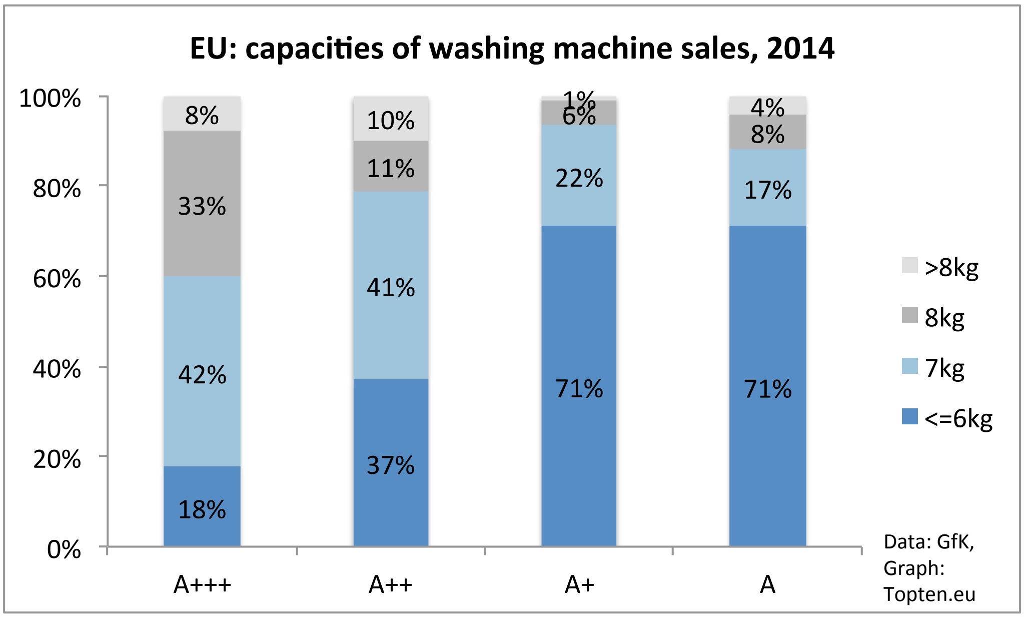

Fig. 8: Efficient washing machines are large washing machines

Figures 7 and 8 show energy consumption and size differences between efficiency classes. The reduction in energy consumption between the classes is small to nearly non-existent: the average declared energy consumption of all class A+ and A++ washing machines that were sold in 2014 is virtually the same. There are two reasons for the small differences in energy consumption: First,.washing machines sold in the two top efficiency classes have clearly larger capacities than A+ and A models. Efficient washing machines are larger washing machines – the larger load leads to a relative increase in consumption and weakens the effect of higher efficiency. Second: the efficiency steps between the classes are not large. Our calculations show that a difference of four classes (A to A+++) results in a reduction in energy consumption of 23% only. In the case of refrigerators for example, this reduction is achieved with a step of one single class [6].

While these declared energy consumption values are valuable for comparing models with each other, they however bear little evidence of how much energy washing machines are consuming in reality, when users choose programmes different from the test programmes or fill their 8-kg-machines with 2kg only. Larger washing machines certainly bear the risk of wasting more energy than smaller ones.

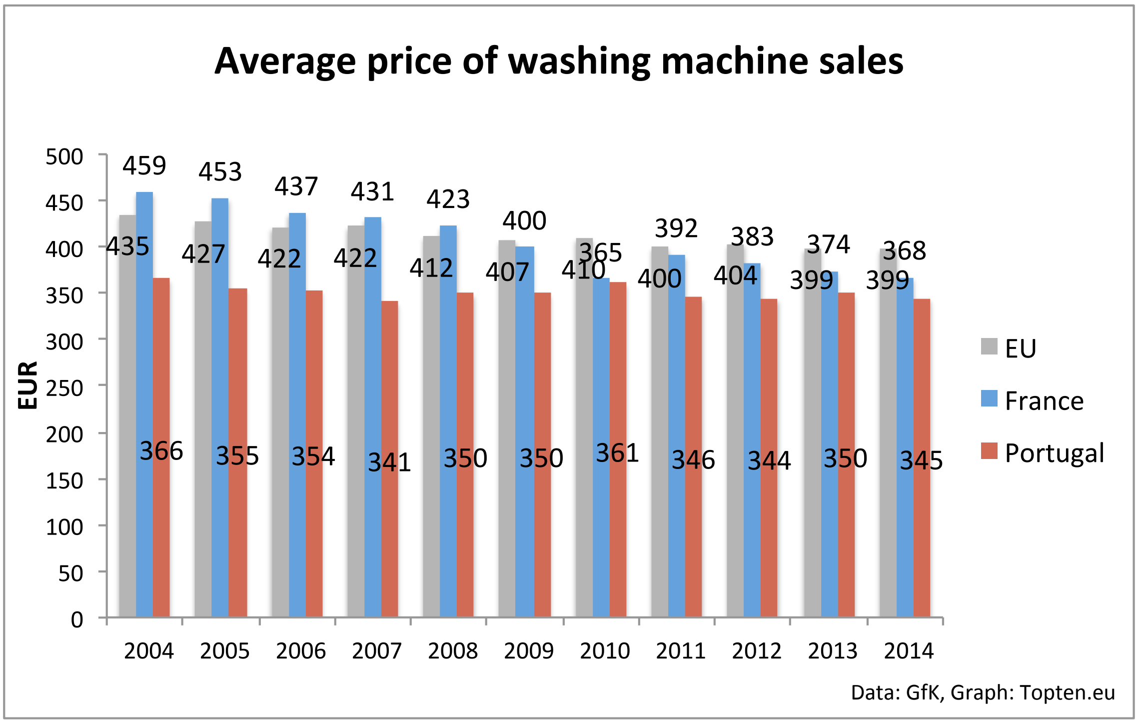

Fig. 6: Average real prices have declined, despite higher efficiency and larger capacities.

Across the EU-21, average washing machine real prices have declined by 8% from 2004 to 2014 – despite higher efficiency and larger capacities. In France, the reduction in price was even 20%. In Portugal, where the sold washing machines are larger and more efficient, average prices are lower. The price reduction in ten years was 6% in Portugal. Since 2009, French and Portuguese average prices have been increasingly below the EU average. In 2014, A+++ washing machines cost on average 69% more than A+ washing machines in the EU [11]. Since more efficient washing machines are also larger, this price premium is linked to both energy efficiency and size.

Conclusions

The first glance on figures 1 to 3 shows a successful efficiency improvement on the washing machines market between 2004 and 2014. Some considerations and more detailed analysis however show some problems and raise questions on the real success.

- Between 2004 and 2011, manufacturers had no official possibility to market energy efficient innovations. More than half of the washing machines that were sold in 2009 and 2010 were declared as exceeding the top class A by more than 10%.

- Soon the situation will be the same again: already 43% of the sales were in the top class A+++. Information on www.topten.eu shows that in July 2015, the best washing machine model is exceeding the A+++ threshold by more than 50% (V-Zug Adora SLQ-WP with integrated heat pump. EEI= 22.8).

- The 2010 Energy Label has not stopped the trend to larger washing machines. It still seems to offer an incentive for higher capacities, because larger washing machines can still reach good efficiency levels easier than smaller machines. Combined with small efficiency steps between the classes, this results in doubtful energy savings. This is underlined by the fact that the average energy consumption of the sales in Portugal is higher than in France and the EU, even though Portuguese buy more energy efficient washing machines.

Recommendations: Energy Label revision

The current Energy Label has been implemented too late, and the added classes were not ambitious enough. The ongoing revision must avoid this mistake and define a Label with classes that can encourage the development of more energy-efficient washing machines for several years into the future. In addition, the Label should be re-scaled to the original A-G scheme, which has shown to be most effective in many studies (e.g. [14|), with the top classes reserved for future innovations. Furthermore the efficiency classes, the most important communicative aspect of the Energy Label, must also be the most important aspect defining the energy consumption – more important than capacity. The new energy label for washing machines should stop encouraging larger machines'. Both can be achieved with a progressive reference line (SAEc): the requirements for reaching a specific efficiency level should be higher for larger machines. At the same time it is recommended to include an 'average' or even 'small' load test cycle (3kg or less) into the EEI and energy consumption calculation (see also [15]).

Systematic market monitoring

Through systematic market monitoring of energy-using products, Europe has the opportunity to set new MEPS and labels that truly encourage a trend towards more energy-efficient products. Such a monitoring system would be inexpensive to implement when compared to the vast energy and economic savings that it will enable. It is hard to understand that Europe renounces on the huge benefits of market monitoring: professional market research companies have the data and it does not cost a lot. Analyzing the market on a systematic basis with sound data would be more cost-effective than today's rather chaotic practice. Even if market monitoring on the longer term was based on a mandatory product registration system and on model data, monitoring based on sales data can start now.

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Standards and Labels

Top10 Sticker: A Sufficiency and Efficiency Purchase Guide in China

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Abstract

Topics: Lifestyle and consumer behavior

Key words: Energy Label, life-cycle cost, energy efficiency and sufficiency, China

In the past 10 years, Chinese government has implemented mandatory energy label that covers 28 product categories and financial incentive programs to encourage consumers to purchase energy efficient products. But information such as Energy Efficiency Index (EEI) and technical terms lowered consumers' interest to read and sometimes even confused consumers.

This paper introduces an intuitive purchase guide, Top10 Sticker, which was developed by Top10 (a Swiss oriented NGO focusing on energy efficiency) in China and deployed in 300 flagship stores of China's biggest appliances retailer chain (GOME) in megacities. The design and revision of this sticker were based on Top10's field study in the last two years. Factors such as data readability, life cycle cost and sufficient usage recommendation are integrated to make it a more intuitive tool compared to China mandatory energy label. A survey covering more than 10,000 consumers was carried out by Top10 to better understand Chinese consumers' decision-making process and the key findings are introduced.

These stickers are updated every 6 months to adapt to market changes. Due to the increased market share of big-sized appliances in China, sufficiency issues were tackled and communicated to consumers in a friendly way. At the same time, training programs were designed and in-store salesmen were trained to better explain the sticker and answer consumers' questions.

This paper concludes with suggestions to improve Chinese mandatory energy label and options to encourage retailers to sell energy efficient products and influence consumers to buy and use them reasonably.

Introduction

The total energy consumption of China is accounted for 22% of world's whole consumption [1]. In 2014, household energy consumption in China is 693TWH, 2.2% more than the number in 2013 and it's expected to keep increasing [2].

Chinese government has implemented a variety of policies and rebate programs to tackle increasing trend. On 16th May 2012, ' State Public Service System 12th 5-years plan' lunched a 26.5 billion RMB subsidy program to promote 'energy efficient' household appliances for one whole year [3]. But for some products categories, 90% product models are eligible for the subsidy, which is against the original purpose of this subsidy program: to promote best energy efficiency products and encourage consumers to buy more efficient appliances.

Top10 China raised 5 points regarding how to subsidy EE products in July, 2012[4], including: subsidy should only go to top efficiency products and to encourage consumers to purchase those products, life-cycle cost should be mentioned. Based on these 5 points, Top10 developed an independent version of label: Top10 Sticker.

To make this sticker visible and useful for consumers, Top10 made contact with two biggest appliances store chains in China, one of them showed interests. In March 2013 Top10 China signed a MOU with Gome. Gome is China's largest household appliances store chain, it has more than 1,700 stores and 60 billion RMB sales value annually. The MOU contains 4 parts of cooperation and this paper focuses on one of them: practical studies of Top10 stickers in 300 flagship Gome stores in 4 biggest cities in China: Beijing, Shanghai, Guangzhou and Shenzhen from March 2013 to December 2014.

China Energy Label

China has a mandatory 'China Energy Label' which covers 34 products categories [5], most of which are household appliances, such as: air conditioners, televisions, washing machine, refrigerators, water heaters etc.

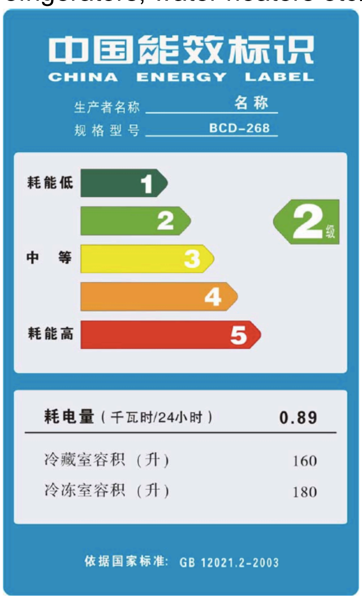

Photo1: Mandatory China Energy Label for refrigerators

The mandatory Energy Label shows in which energy level the product is (level 1 to 5, level 1 is the most efficient while level 5 is the least), and the label contains energy related data such as 'energy efficiency ratio', 'input power', 'seasonal energy efficiency ratio (SEER)'. Some technical data is difficult to understand for general consumers.

Also Energy Label updates every 2 to 3 years, while products in market update much faster.

Design the Sticker

In February 2013, Top10 China started to design Top10 energy saving stickers. The aim of the sticker is to be a useful complement of Energy Label and it should be: easy to read, focus on best efficient products, cover life-cycle cost and update along with market change

First version of Top10 stickers was produced and applied on 1st March 2013. This version is valid for 6 months until 31st August 2013.

This sticker covers 5 product categories:

TVs
Refrigerators
Washing machines
Air conditioners
Water heaters

Photo 2: Top10 in-store sticker (version 1)

For every single product sticker, the following information was provided to consumers:

1: product information 2: energy consumption in 5 years. (In RMB, not in KWH) 3: energy saving in 5 years (In RMB) 4: sufficiency information (suitable for what sized household and room, etc.)

In each category, Top10 selected around 20 products and in total around 100 product stickers. Those stickers were applied in 300 Gome stores in Beijing, Shanghai, Guangzhou and Shenzhen (4 biggest cities in China) with the support of Gome headquarter.

The information contains in the sticker transfers energy saved in Kilowatt-hours into money saved. It's easier to understand and more direct for consumers.

Also those stickers give advice for a sufficient phrasing. E.g.: a 220L capacity refrigerator is recommended for households with 2-3 person; a 40 inch sized television is recommended for living rooms with 3.5-4 meter watching distance. The purpose is to advice people to buy not only efficient products, but also sufficient products for their households.

Product type and technical data were also provided in the sticker but using smaller font.

Photo 3: Products in Gome stores with Top10 stickers, 2013.05, HUANG Luting, Top10 China

Development of Sticker

To better understand consumers' needs, Top10 worked with 'China Consumer Newspaper' in June 2013, sent out a questionnaire to research consumers' opinions about mandatory energy label and how they make decisions when they are making a purchase.

12,519 consumers participated. 65% consumers never check the data on energy label because they couldn't understand; 85% consumers will consider life cycle cost if they were told about it. There is also some basic confusion such as: 25% consumers think if a product has an energy label, it means it's an energy efficient product; 27% consumers even think level 5 is the best energy efficient.

The research indicated that although the mandatory China Energy Label has been running for over 9 years since 2004, there is still a number of consumers are not aware of it, or not completely understand it. The most important finding of this research is that consumers are not sensitive to the technical data showing on the label, because for most of them it's difficult to understand what those data means.

These findings are consistent with the principle of Top10 sticker: easy to read; life-cycle cost and only focus on best products.

Also a small-scaled face-to-face survey was carried out with 40 Gome salesmen, who have the first hand experience dealing with consumers in store. They gave a lot practical suggestions, such as: in the sticker, a product's total energy consumption within 5 years was calculated but for consumers, annual energy consumption might make more sense; for some products, the period to calculate total energy saving should be adjusted to fit consumers using habits. 32 salesmen thought this sticker is a good help to both sell products and help consumers.

On 15th September 2013, the 2nd version sticker was released. New version was valid from 15th September 2013 to 31st March 2014. The outlook and structure remains but there were some mineral changes on energy consumption and energy savings, for instance, energy consumption data has changed from 5 years to 1 year, according to salesmen's feedback.

Photo 4(left): Top10 in-store sticker (V2) Photo 5 (right): Top10 in-store sticker (V3)

On 30th June 2014, the 3rd version sticker was applied and valid until 31st December 2014. The new version had a new color scheme because Top10 China changed its logo and color. Besides tis, there were 2 main changes:
1: Add a QR code. Consumers can scan the QR code and be directed to Top10 website to check more details.
2: The money saving information is more visible. This is the most interesting information for consumers.

Photo 6: Products in Gome stores with Top10 stickers, 2014.08 by: ZHAO Feiyan, Top10 China.

The market influence of Top10 stickers

Because of business confidential consideration, the detailed sales data is difficult to obtain from retailers, but they provided sales ranking list before and after the sticker period. In total, 55% of Top10 labeled products' ranking is increased, 43% is decreased and 2% remains. This result is also influenced by market change, seasonal promotion and other elements.

From the feedback of salesmen, people who noticed Top10 stickers showed interests and the life cycle cost saving will especially influence price-sensitive consumers.

Also in the June 2013 consumer research was very encouraging that 89.5% consumers indicated that besides government's mandatory label, the independent, third party advice is valuable and needed when they are making decisions.

Learning and Conclusion

Sticker	Number of product category	Number of product model	Valid days
Version 1	5	96	184
Version 2	5	95	196
Version 3	5	106	185

From 1st March 2014 to 31st December 2014, this in-store, on-product Top10 sticker was implied for 565 days, on 95-106 product models in 5 main household appliances categories, it covered 4 main cities in China.

Top10 sticker contains two important messages: sufficiency and efficiency. It advises consumers to buy energy efficient appliances that are sufficient their household needs. It calculates the total energy saving while using a certain product, to counterbalance a relatively higher buying price.

To better understand and develop the sticker, research of consumers and salesmen were carried out and some valuable suggestions are taken in improving the next version sticker.

From the feedback of salesmen, the consumer survey result and sales data, we can say Top10 sticker is a useful tool for consumers to identify best products and to make sufficient and efficient purchase, and it's very important to have a third party independent voice beside mandatory Energy Label. The sticker also helps on selling products but the influence is not very significant.

There are also some inadequacies:

1: Top10 sticker focuses only on best efficient products and selects around 20 market-available product models from each category. But in practical, it is very unlikely to have all the 20 models displayed in one store because space in store is limited, manufacturers will only choose what they want to promote most to display in store. Especially in different cities, branch stores' display preference vary a lot.

2: Manufacturers are not encouraged enough. In Chinese household appliance retailer stores, the normal situation is manufacturers send their staff to sell products in store, together with retailer salesmen. It's like a 'stores in store'. The cooperation was between Top10 and retailer, there was no direct communication between Top10 and individual brands. If manufacturers were more involved and gave focused display or special promotion to products with Top10 stickers, the influence will be emphasized.

In conclusion, Top10 sticker is a useful tool for consumers to identify the best energy efficient and sufficient appliances and it's a complement for mandatory Energy Label. It's helpful for retailers because it's a new selling point with third-party endorsement and it's useful for consumers because it provides easy and unbiased recommendation. How to involved manufacturers and how to select products will need to be developed in future.

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Appliance Labeling for the 21st Century: Introducing QR code for the China Energy Label[1]

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Abstract:

Energy labels have been a fundamental and highly effective tool for appliance efficiency programs globally. They are affixed to appliances and/or their packaging, and are designed to inform consumers about product energy performance and influence purchasing decisions. Energy labels are either categorical, identifying a tier or ranking (e.g. A, B, or C, or 1 to 5 stars), or serve as an endorsement, indicating that a product is an efficient model on the market. Due to their physical size restrictions, energy labels can only provide a limited amount of information, thus limiting their potential impact on consumer decision making. Also, market supervisors need to manually type the information on the label through internet into their electronic devices to check its conformity against registration database and that makes it very challenging for market surveillance.

Recognizing the issues mentioned above, and seeking to capitalize on both very high awareness of the China Energy Label and the high penetration rate of smart phones among Chinese consumers, China has started to attach QR codes to the China Energy Label. A QR code is a digital technology that consumers can scan with their smart phones to gain more detailed information about a product's energy performance and compliance with applicable regulations. QR codes carry a much greater amount of information than that conveyed by a standard physical label.

This paper explores the process by which QR codes were introduced and implemented as part of the China Energy Label, and discusses the potential impact of QR codes on consumer purchasing behavior.

1. Introduction

The China Energy Label (CEL) celebrated its 10th anniversary in March 2015. The CEL is an informative label that is attached to a product or its packaging, providing consumers with information about a product's efficiency level, enabling them to make purchasing decisions that favor higher efficiency products.

The rapid development of information technology (IT), particularly the accelerated penetration of smart phones and other mobile devices into the Chinese market, has created a strong foundation from which the CEL can upgrade its application. The use of IT methodologies to promote the CEL and improve the label's provision of information has become the research focus of the CEL's administrative agencies.

This paper explores the process by which QR codes have been introduced and implemented as part of the CEL and is structured as follows:

The application and achievement of the current CEL;

- Examples of QR code application;
- Feasibility study of the application of QR codes on the CEL;

[1] Industry Research Project for Quality Control (201410002),supported by General Administration of Quality Supervision, Inspection and Quarantine of the People's Republic of China (AQSIQ), and implemented by China National Institute of Standardization (CNIS).

- Design of CEL with QR codes and process of enforcement;
- Summary and recommendations

2. The application and achievement of the current CEL

Over the past decade, the CEL has expanded to cover a wide range of products. For each product, the CEL displays information on the manufacturer, model number, energy efficiency tier (three or five[2]), key energy efficiency indicators (for example, refrigerator's label includes energy consumption, freezer volume, cold room volume), and the energy efficiency standard that is referenced. It features a simple design, using white as the primary color (see Figure 1). The label helps consumers make informed purchase decisions, and provides market supervision agencies with information on product energy efficiency.

Figure 1 Example of Current China Energy Label

By November 2014, the CEL covered twenty-nine products in five categories, including household appliances, industrial products, office equipment & electronics, commercial equipment, and lighting products. The label was featured on products from over 9,000 manufacturers. According to market research on consumers' awareness of the CEL, conducted by CLASP in 2013, 97.3% of urban consumers claim that they have seen the label. [1]

Due to limitations in its physical size, the current CEL cannot provide sufficient important information to consumers. For example, consumers probably have difficulties understanding of certain technical terms or energy efficiency indicators [1], such as TV Energy Efficiency Index (EEI). However, there is no room to provide explanations for some of these terms.

A similar problem arises when it comes to enabling consumers to differentiate between products assigned to the same energy efficiency tier. In China, energy efficiency standard is lagging product development. Therefore, the market share of Tier 1 models (the most efficient models available on the Chinese market) is very large for most product types, sometimes accounting for up to 94% of models. However, even though the most efficient Tier 1 model for some products could be over 70%[3] more efficient than the least efficient Tier 1 model, consumers may not be able to differentiate between the energy performances of these models. Consumers would need more information to make better

[2] When developing levels of energy efficiency requirements, if market research shows the energy efficiency gap is big enough to include five tier between the most efficient model and the least efficient model (MEPS level), a five-tier scheme will be applied to this product. Otherwise, three-tier scheme will be applied.

[3] Calculated from data of refrigerators under Market Analysis of China Energy Efficient Products (MACEEP), CLASP and Top10 China, 2013

informed purchase decisions that fully account for the efficiency of different products, but the limited size of the CEL means that this information is not always available or clearly communicated.

In the past a few years, mobile devices such as smart phones have been widely adopted by Chinese consumers, providing an opportunity for the CEL to apply IT measures to better serve Chinese consumers, market supervisors, and other stakeholders. Exploring these potential IT measures to improve the CEL has been a priority for CEL management agencies.

3. Examples of QR code applications

The use of QR codes in China began in 2006, meaning that the technology has had time to evolve and mature. The technology has been applied in a variety of settings – for example, on train tickets and groceries, as shown in Figure 2 – helping to improve the consumer experience, enhance management effectiveness, and lower inspection costs. These examples serve well as references for the use of QR codes as part of the CEL.

Figure 2 QR code applications in train tickets and food

4. Feasibility study of the application of QR codes on the CEL

4.1 Feasibility study on enforcement

The CEL is implemented through three primary mechanisms: (1) manufacturer self-declaration, (2) product registration, and (3) after-registration monitoring. Manufacturer self-declaration is the key element of the program, whereby manufacturers are responsible for the accuracy of the information of their products and subject to market supervision. Registration is the way how administrative agencies manage the CEL scheme. Manufacturers register their products by providing the required data and information. Such data and information is then selectively printed on the label and shown to consumers. “Registration” works as a tool connecting manufacturers, administrations and consumers, and also serves as the database used for the verification of product information. After-registration monitoring is the method employed to safeguard the credibility of the CEL scheme, ensuring that manufacturers are not able to manipulate product data in order to benefit themselves.

During each of these stages, the CEL scheme can be implemented more smoothly and effectively by applying new IT solutions such as QR codes. Using QR codes can expand the amount of product information that is made available to consumers, as well as enable real-time information requests. There has been support among manufacturers, administrations and consumers for these kinds of improvements, and the maturation of QR code technology paved the way for its application as part of the CEL program.

4.2 Feasibility study on technology

A QR code is a square pattern, most commonly observed in black and white. QR codes can contain 4,296 letters or 984 Chinese characters. Applied to the CEL, a QR code could either contain detailed product information, or direct the scanner to a web link where detailed product information was available. A QR code can be pointed to a web link so long as the CEL has product data available that can be displayed on a web page.

4.3 Feasibility study on data availability

Digitizing product information has been a priority when new products have been registered with the CEL, and the CEL management center has maintained a database of this product data since 2005. This effort solves one of the biggest challenges in applying IT solutions to the CEL: the establishment of an electronic product database. Consequently, all that is needed now is to assign a QR code to each product in the database. New products will be assigned a QR code when they are registered with the CEL.

4.4 Feasibility study on promotional activities

The use of QR codes is simple and convenient. After a registered product has been assigned a QR code – with the QR code pattern containing either product information or a web link – consumers can then use QR code-scanning software, which is already integrated into many smart phone Apps, to scan the pattern and access the relevant product information.

According to statistics from the Chinese Ministry of Industry and Information Technology (MIIT), the number of mobile phone users in China as of May 2014 had reached 1.256 billion, accounting for 90.8% of the population. Among all users, 470 million surfed the internet with mobile phones.[3] Overall, the high rate of smart phone ownership and use in China means that consumers are well equipped to interact with the QR codes as part the CEL.

5. Design of CEL with QR code and process of enforcement

5.1 Design of CEL with QR code

The CEL is a vehicle for delivering information to consumers. Good label design is a key factor in a label's success. Established standards for good label design include:

- the design is visually attractive, in order to quickly draw a consumer's attention;
- information is clearly presented, with important information (such as energy efficiency tier number) highlighted; and
- information is easy to understand.

Considering that 97.3% of consumers recognize the existing CEL, and the possibility that consumers might be slow to adapt to change, significant alterations to the current design could have caused confusion and undermined the CEL's impact. Therefore, the QR code has simply been added to the bottom of the existing label (see Figure 4).

Figure 3 Example of CEL with QR code

Furthermore, because the QR code is currently a voluntary measure, the QR code portion of the CEL is detachable, and can be removed from the CEL if a particular manufacturer does not use QR codes.

From Jan 2015 to June 2015 there are 6 manufacturers, 514 models using QR codes CEL, and have got more than 60,000 scans.

5.2 Process design for QR code implementation

Based on the descriptions above, it is clear that QR codes are a valuable resource for the CEL. QR codes allow the CEL to transcend the size constraints of a physical label in order to provide additional useful information. QR codes are also cost-effective and will not interfere with consumer's ability to recognize the CEL. When applied to the CEL, QR codes:

- Define and explain important technical terms;
- Provide a channel for manufacturers to market their products;
- Simplify the market supervision work cycle;

Implementing a QR code scheme as part of the CEL follows the process illustrated in Figure 5.

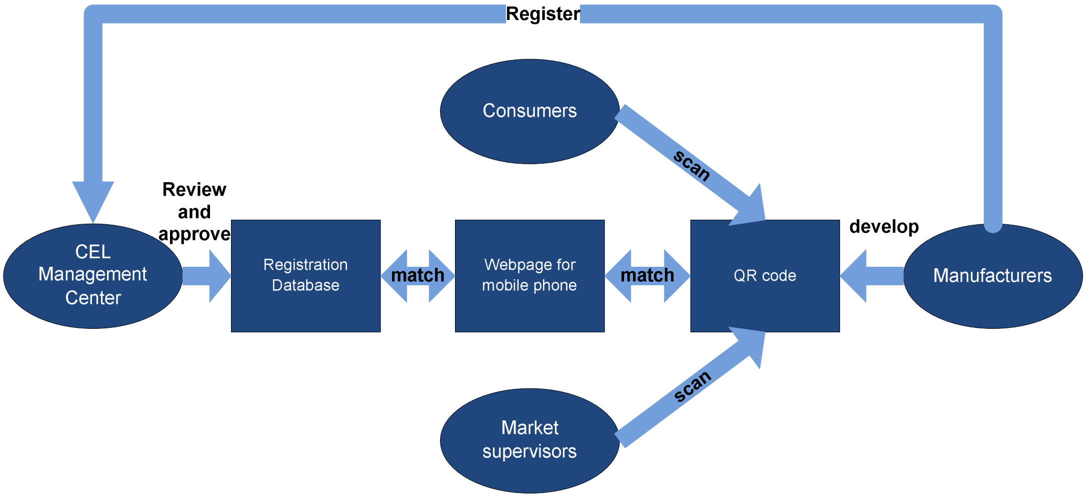

Figure 4 Process of using CEL with QR code

Presently, if a manufacturer wants to use a QR code on their products' label, they need to get a QR code from the CEL official website, for their product when they register under the CEL. The CEL is implemented based on the "Energy Efficiency Label Management Method", and QR codes will not be mandatory for manufacturers until this Method is officially revised. [2]

5.3 Primary information from scanning a QR code

Currently, the QR code for a specific product model contains a web link, pointing to a web page that displays all registered data and information about the model scanned. Figure 6 shows an example of the information presented on these web pages.

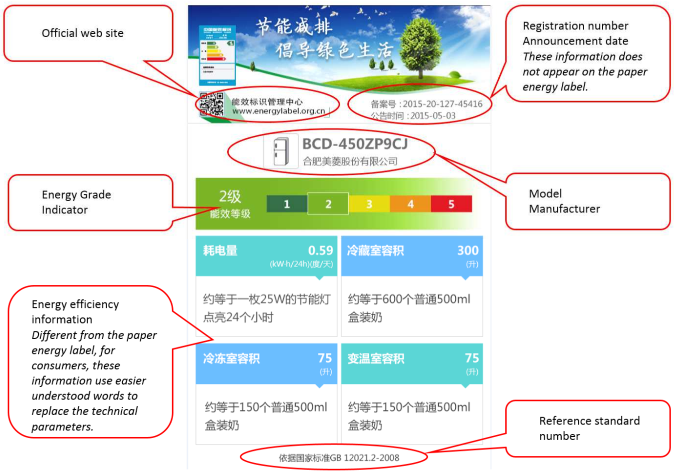

Figure 5 Example of QR code scanning result

The webpage is structured in modules, in order to make key messages more obvious to consumers and market supervisors.

6. Summary and recommendation

This paper discussed the application of QR codes to the existing China Energy Label and examined the feasibility of implementing QR codes from the perspectives of enforcement, technology, and data management. The paper also described the design of the CEL with QR codes included, the new process for CEL implementation with QR codes, and the types of information that QR codes provide. The following conclusions can be made:

1. The maturation of information technology and the high penetration of smart phones among Chinese consumers have allowed QR codes to be effectively applied to the CEL;

2. Based on China’s experience to date, QR codes have improved the management of the CEL by relevant administrative bodies, provided manufacturers with a useful channel for marketing their products, and lowered the cost of market supervision.

In order to advance the application of QR codes under the CEL, the following steps must be taken:

1. Accelerate the market adoption of QR codes by both manufacturers and consumers;

2. Revise the “Energy Efficiency Label Management Method” to make QR codes a mandatory CEL measure.

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Consumer Comprehension of the China Energy Label and Household Appliance-using Habits in China

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Abstract

In 2005, China introduced a mandatory labeling program to promote energy efficient products. The China Energy Label (CEL) now covers over 30 product categories. Two studies were conducted recently on consumer awareness and comprehension of the CEL and household appliance-using habits. The objectives of the studies were as follows:

- To understand urban consumer views and attitudes towards the CEL, including their general understanding of the label, its design and specific parameters; and seek suggestions and recommendations from consumers for improvement of label design and information;

- To understand the appliance-using habits in urban Chinese households, including frequency, duration and other relevant information, which can all be used in facilitating improvements in test methods and calculating energy saving potential.

The results of the consumer awareness and comprehension study indicate that Chinese consumers have a high level of overall awareness of the CEL. However, their level of awareness varies greatly among different appliances. For example, awareness of refrigerator labeling is 96%, while awareness of labels on laptop computer is 10%. While consumers indicated that the technical terms used on the CEL were important to them, they demonstrated a higher level of understanding for simpler terms such as energy consumption for refrigerators than more complicated terms such as 24 hour standby energy loss index for electric storage water heater. The results of the study will be highly useful in revising the CEL to better inform consumers and influence purchasing decisions.
The consumer usage study, which is the first of its kind in China, found that household electricity consumption is between 84 and 175 kwh/month. This is much lower than developed countries such as US, where the average residential electricity consumption is over 900 kwh/month. The study results indicate that Chinese consumers are very conscious about their electricity consumption, and that a high percentage of homes choose to unplug appliances immediately after use. A variety of appliance-using habits, such as number of loads per week for clothes washers, duration for TV viewing, and the temperature setting for water heaters, were also recorded as part of the study and this data will be highly useful in improving the "real world" accuracy of product test methods and calculating energy savings potential from appliance standards.

Introduction

China is the largest manufacturer and consumer of household appliances in the world. China's fast-growing economy and accelerating urbanization process have benefited the population enormously over the past few decades, with better living standards and more disposable income. As a result, demand for household appliances is increasing, as is the amount of energy consumed by those appliances.

The Chinese Government has long recognized the importance of energy-saving potentials from appliances. Since the 1980s, China has implemented over 50 minimum energy performance standards (MEPS). In 2005, China launched its mandatory China Energy Label (CEL) program, which now covers over 30 product categories. These two programs have greatly contributed to market transformation towards highly efficient appliances. As the programs continue to cover more products and gain more exposure to the public, more and more consumers are becoming aware of the CEL and reference it in the decision-making process when purchasing appliances.

In order to understand the degree to which consumers comprehend the CEL, as well as how appliances are used in typical urban Chinese households, a market research study was recently conducted. The first part of this study is the label comprehension study and the second part is the appliance-using habits study. Specific research objectives are as follows:

- To understand urban consumer views and attitudes towards the CEL, including their general understanding of the label, its design and specific parameters; and seek suggestions and recommendations from consumers for improvement of label design and information;
- To understand the appliance-using habits in urban Chinese households, including frequency, duration and other relevant information, which can all be used in facilitating improvements in test methods and calculating energy saving potential.

For the label comprehension study, consumer comprehension of CEL was investigated for nine types of household appliances, namely refrigerators, washing machines, televisions, water heaters, induction cookers, rice cookers, microwaves, computers (including monitors) and air conditioners. The appliance-using habits study examines how appliances are being used in typical Chinese households. The paper concludes with a set of policy recommendations based on the research findings.

Methodology

As discussed above, this study was divided in two parts, each of which has its own specific objectives. As such, different methodologies were employed in carrying out this study. Table 1 summarizes the methodologies used for each part of the study.

Table 1: Methodology overview

Objective	Online questionnaire	Personal interview	Home visit	Appliance "diary"
label comprehension study	✓	✓		
appliance-using habits study			✓	✓

Online questionnaires:

This was the primary method used in assessing consumer comprehension of the China' Energy Label. An online questionnaire was designed and distributed to a pool of selected respondents from different cities across varying ages, genders, income levels, and education backgrounds.

Personal interviews:

Recognizing that the online questionnaire respondents were mostly young and middle- aged consumers who were considered more "internet-savvy," we supplemented the online survey with personal interviews of elderlies (age 60 or above). Elderlies were intercepted for interviews at various locations such as parks, community centers, and news stands. The questionnaire used for personal interviews was exactly the same as the online questionnaire.

Home visits:

For each household that participated in the appliance-using habits study, one trained interviewer was sent to conduct a home visit. The purpose of the home visit was to survey the different types of appliances used in each household (including brand, model, technical parameters, and photos) and to train the household member who was responsible for this study how to record their appliance-using habits using a pre-designed diary.

Appliance diary:

The household participants were required to record their appliance-using habits for one entire week using the pre-designed diary. The recording period took place from October 19 to 25, 2013. Nine types of primary household appliances were included in the diary, namely refrigerators, washing machines, televisions, water heaters, induction cookers, rice cookers, microwaves, computers (including monitors), and air conditioners. Participants were only required to complete the diary for appliances that they owned.

Methodology for Label Comprehension Study

Questionnaire design

The label comprehension questionnaire was comprised of two parts. The first part aimed to examine consumers' general understanding of the CEL, with reference to the following points:

- Whether consumers had seen the China Energy Label;
- On which type of appliances consumers saw the label;
- Whether consumers understood the classification of energy efficiency tiers on the label;
- Whether consumers were able to differentiate between highly efficient and less efficient products;
- What information on the labels consumers considered the most important; and
- Other relevant information.

The second part of the questionnaire assessed consumers' understanding of each of the technical parameters (such as "rated volume" or "24 hour energy consumption") included on the label for some specific products. For each technical parameter, consumers were first asked whether they understood the meaning of the parameter; they were then asked to answer a specific question regarding that parameter to test whether or not they genuinely understood it.

Sampling

1281 survey respondents were selected from six regions in China. The number of respondents from each region was proportional to its regional population (see Table 2). Since the online survey respondents were mostly between the ages of 25 and 60, we also conducted face-to-face interviews for elderlies over 60 years of age (see Table 3). The number of online and elderly respondents were 1100 and 181, respectively, for a grand total of 1281 participants.

Table 2: Regional Distribution of Online Survey Respondents

Region	Province/city	# of Respondents
North China	Beijing, Tianjin, Hebei, Shanxi, Inner Mongolia	136
Northeast	Heilongjiang, Jilin, Liaoning	115
East China	Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong	353
Mid-South	Henan, Hubei, Hunan, Guangdong, Guangxi, Hainan, Shenzhen	296
Southwest	Chongqing, Sichuan, Yunnan, Guizhou,Xizang	126
Northwest	Shaanxi, Gansu, Qinghai, Ningxia, Xinjiang	74
Total		1100

Table 3: Regional Distribution of Elderly Survey Respondents

Region	Province/city	Respondents

North China	Beijing	31
Northeast	Shenyang	30
East China	Shanghai	30
Mid-South	Guangzhou	30
Southwest	Chengdu	30
Northwest	Xi'an	30
Total		181

The project team determined that the questionnaire would be too lengthy for the respondents if all nine product types covered in the survey were included in one questionnaire. Therefore, we randomly divided the respondents into two groups, with Group A being surveyed for four types of products and Group B for the other five, as shown in Table 4 below.

Table 4: Respondent Distribution by product group

Group	Products	# of respondents
A	Refrigerator, television, water heater, rice cooker, microwave	642
B	Washing machine, induction cooker, computer (monitor), air conditioner	639

Methodology for Appliance-using Habits Study

Home visits and diary-recording

A combination of home visits and diary-recording was used in the study of appliance-using habits in Chinese households. One of the primary users of appliances in each participating family was required to keep record of how they used their appliance every day for one entire week. The team designed a diary (see **Error! Reference source not found.**) to help consumers record their appliance-using habits, including factors such as frequency and duration of use, temperature settings, time in standby mode, and whether or not the appliance was unplugged after use.

Prior to the diary recording process, trained project coordinators visited the home of each participating family to survey the appliances used and to train the designated family member – the main user of the selected appliances with the greatest understanding of how to use them – on how to record in the diary. The coordinators also followed up with each participating family by phone on the first day of the recording period and every other day after that. These calls helped the coordinators to ensure that the families were recording the diary properly, as well as answer any questions raised. The coordinators collected the diaries from the families the day after the last day of the recording period.

Sampling

A total number of 215 families were selected from six cities – one from each of the six regions in China. The sample covered various family member structures and income levels. At least 30 families had to be selected in each city in order for the samples to be statistically significant. Table 5 shows the distribution of the number of participating families in each city in this study.

Table 5: Regional Distribution of Participating Families in Appliance-using Habits Study

Region	Province/city	# of families
North China	Beijing	51
Northeast	Guangzhou	34
East China	Nanjing	33
Mid-South	Chengdu	34
Southwest	Xianyang	32
Northwest	Jinzhou	31
Total		215

Consumer Comprehension of the China Energy Label

General Awareness & Understanding

Recognition of labels for different appliances

Consumer label awareness for different appliances varied. The top-ranking appliances in terms of label recognition are all primary appliances – e.g. air conditioners, washing machines, televisions, and electrical water heaters – which were included in the early phase of China's energy labeling program. Refrigerators had the highest rate of recognition; over 96% of respondents claimed that they had seen the refrigerator energy label. However, recognition among consumers was found to be much lower for computers and microwaves (see Figure 1). This is most likely due to the fact that these products entered the labeling program more recently, in 2012 and 2011 respectively.

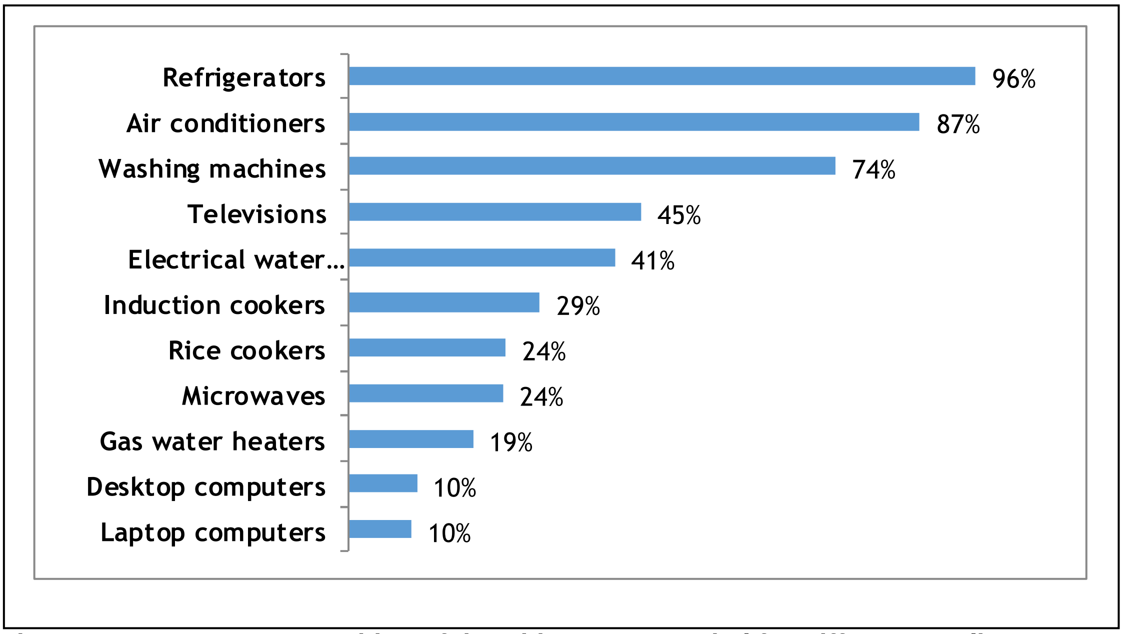


Figure 1: Consumer Recognition of the China Energy Label for Different Appliances

Understanding of energy efficiency tiers

The CEL is a categorical label with three or five energy efficiency tiers for different appliances. Tier 1 represents the highest level of energy efficiency, while Tier 3 or Tier 5 – whichever one is the lowest tier on the label – represents the minimum energy performance requirement.

In order to assess Chinese consumers' understanding of the energy labeling tiers, survey respondents were asked to identify the tier that represented the highest energy efficiency level. Overall, 75% of the respondents were able to identify Tier 1 as representing the highest level of energy efficiency; however, as shown in **Error! Reference source not found.** below, 13% of respondents thought that Tier 5 was the highest.

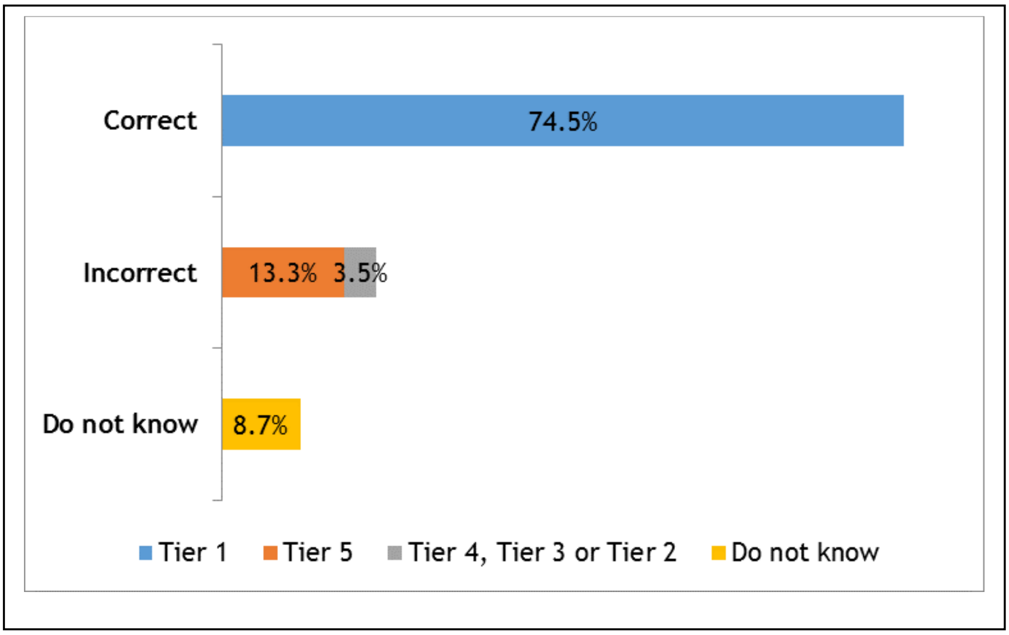
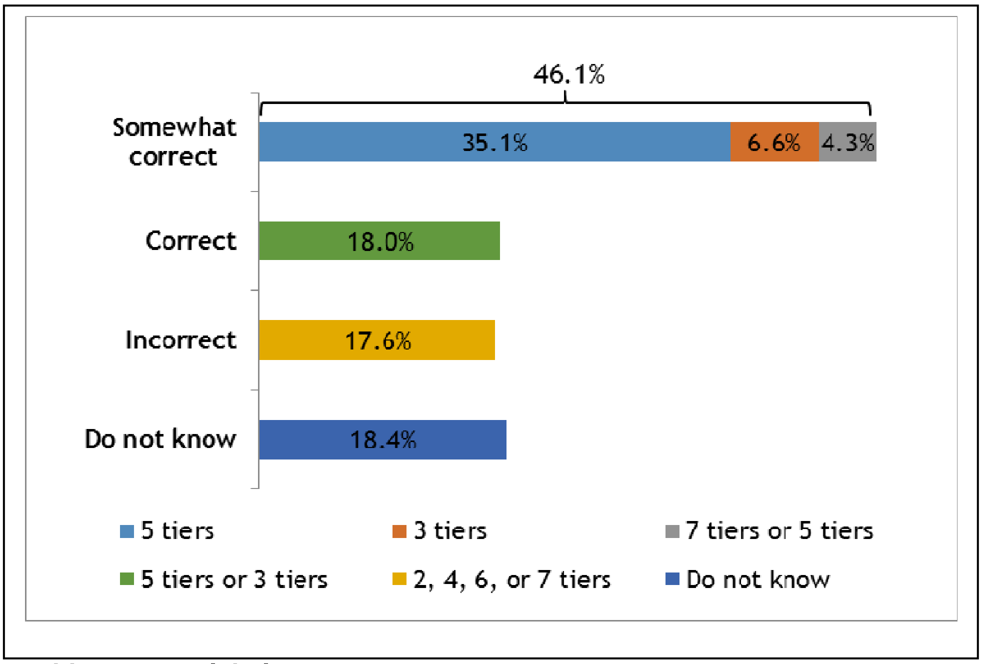


Figure 2: Consumer Comprehension of the Highest Energy Efficiency Tier - "Which tier represents the highest energy efficiency?"

The survey results also demonstrated that different tier classifications for different appliances are a source of confusion among consumers. Only 18% of respondents knew that labels for some appliances have three tiers, while others have five tiers. As shown in Figure 2 below, a large proportion of respondents (35%) thought that all labels had five tiers. This is understandable when we consider that refrigerators labels, the most widely recognized among consumers, have five tiers.

Figure 2: Consumer Comprehension of Different Labeling Tiers - "How many tiers are there



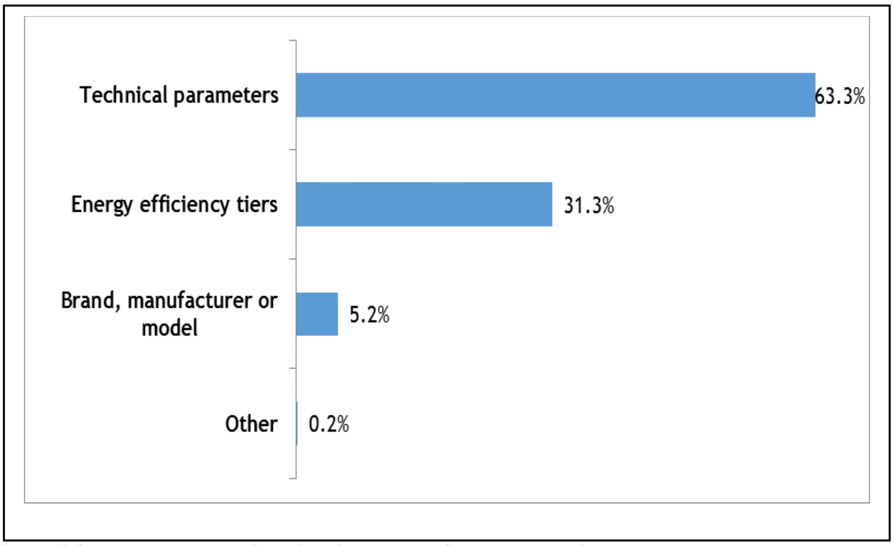
on China energy labels?"

Overall, these results indicate that while Chinese consumers have a certain level of understanding about the CEL, promotion and education efforts must be furthered in order to improve comprehension.

Information on the label

The survey also revealed that Chinese consumers care about the technical parameters provided on the labels more than the energy efficiency tiers. Approximately two-thirds of respondents indicated that technical parameters were the most important information on the labels, as shown in Figure 3 below. At the same time, approximately 35% of respondents thought that some of the technical parameters were too difficult for average consumers to understand, especially among elderlies. Forty percent of consumers expressed that some of the current labels did not directly show the energy consumption by appliances.

Figure 3: Consumer Priorities on Energy Label Information - "What information provided on



the China Energy Label is the most important for you?"

The results indicated that technical parameters were very important for consumers, but they had to be easily understood. In addition, consumers would like to see more information on energy consumption and energy or cost savings to help them make an informed choice when purchasing appliances.

Comprehension of Technical Parameters

The label comprehension survey also focused on specific technical parameters provided on the CEL for various products. For each parameter, we first asked respondents to state whether or not they thought they understood the parameter. They were then asked to answer a specific question regarding this parameter to test whether or not they actually did understand the parameter correctly. For example, respondents were shown the labels for two separate refrigerators and were asked to identify the product that consumed less energy.

Table 6 shows the percentage of respondents who correctly answered the question, demonstrating that they understood the parameter.

Table 6: Consumer Comprehension of Technical Parameters on Product Labels

Appliance	Parameter	Respondents Who Correctly Understood the Parameter
Refrigerator	Refrigerator volume (L)	80.8%
	Freezer volume (L)	80.8%
	Energy consumption	62.0%
Washing machine	Washing capacity (kg)	71.7%
	Water consumption (L/cycle)	68.8%
	Cleaning ratio	30.2%
Television	Standby power (W)	34.9%
	Energy efficiency Index (EEILCD or EEIPDP)	8.4%
Water heater	24hour standby energy loss index (ε)	27.0%
	Hot water production rate (μ)	21.8%
	Rated heat input (kW)	17.9%
	Hot water production efficiency at rated heat input	15.1%
Induction cooker	Standby power (W)	48.5%
	Thermal efficiency (%)	48.2%

Rice cooker	Standby energy loss (Watt hours)	59.2%
	Keep warm energy consumption (Watt hours)	58.7%
	Thermal efficiency (%)	38.5%
	Inner container material (metallic or non-metallic)	9.5%
Microwave	Standby power loss (W)	61.7%
	Off-mode power loss (W)	48.9%
	Efficiency (%)	43.8%
	Barbecue mode energy consumption (Watt hours)	20.4%
Computer	Off-mode energy loss (W)	53.7%
	Product type (A, B, C, or D)	12.8%
	Energy efficiency (cd/W)	45.4
Air conditioner	Cooling capacity (W)	44.0%
	Rated cooling capacity (W)	40.7%
	Input power (W)	31.0%
	Annual energy consumption efficiency (%)	21.0%
	Cooling season energy consumption (kWh)	7.6%
	Energy efficiency index	7.5%
	Heating season energy consumption (kWh)	6.7%

As shown above, respondents' comprehension varied greatly for different technical parameters and different appliances. We attempted to divide these parameters into five different categories in order to conduct a clearer analysis:

1. **Physical parameters**: Parameters related to the physical properties of the appliance. These parameters include, refrigerator volume (L), freezer volume (L), washing capacity (kg/cycle) for washing machines, inner container material (metallic or non-metallic for rice cookers) and product type for personal computers (type A, B, C or D).

2. **Simple energy consumption parameters**: Parameters related to energy consumption that use simple expressions such as "energy consumption," "standby loss," and "power." These parameters include energy consumption for fridge, water consumption for washing machines, standby power for TVs, standby power for induction cookers, keep warm energy consumption for rice cookers, standby power loss and off-mode power loss for microwaves, off-mode power loss for computers, and cooling capacity and power input for air-conditioners.

3. **Complicated energy consumption parameters**: Parameters related to energy consumption that use more complicated expressions. Complicated energy consumption parameters include rated heat input for water heaters, barbecue mode energy consumption for microwaves, and cooling season energy consumption and heating season energy consumption for ACs.

4. **Efficiency parameters**: Parameters related to efficiencies, such as hot water production efficiency and thermal efficiency. These parameters are normally expressed as a percentage. Efficiency parameters include cleaning ratio for clothes washers, hot water production rate and hot water production efficiency at rated heat input for water heaters, thermal efficiency for induction cookers, thermal efficiency for rice cookers, efficiency for microwave, energy efficiency for computers and annual energy consumption efficiency for ACs.

5. **Index parameters**: Parameters such as energy efficiency index (EEI) and energy efficiency ratio. These parameters are normally unit-less. Index parameters include energy efficiency index for TVs, 24-hour standby energy loss index for water heaters and energy efficiency index for ACs.

The following figures illustrate respondents' comprehension the different parameter types.

Physical parameters

The results showed that Chinese consumers demonstrate rather high levels of comprehension about physical parameters on the CEL overall. A high percentage of respondents who claimed that they understood the parameters could also answer the specific questions correctly.

However, consumers demonstrated very low levels of comprehension on “product type” for computers and “inner container material” for rice cookers. Computers are divided into four product types on the CEL – A, B, C, and D – based on their central and graphics processing units (CPUs and GPUs). This is significant because energy efficiency tier requirements sometimes differ for different product types. Similarly, inner containers for rice cookers can be either metallic or non-metallic, and the minimum energy performance requirements differ between these two types. Evidently, average consumers do not possess the knowledge of such information and therefore it was difficult for them to understand these parameters.

Simple energy consumption parameters

Simple energy consumption parameters such as energy consumption, standby energy loss, cooling capacity, and input power, appear to be well-understood among Chinese consumers. Approximately 60% to 80% of consumers were able to correctly answer the questions regarding simple energy consumption parameters.

Complicated Energy Consumption Parameters

These more complicated energy consumption parameters appeared to be less familiar and straightforward for consumers. For example, it was difficult for respondents to understand what “cooling season” energy consumption or “barbecue mode” energy consumption referred to. As such, levels of comprehension for these parameters were low – approximately 20% on average.

Efficiency Parameters

On average, approximately 40% of survey respondents were able to correctly answer the questions regarding efficiency parameters. Consumers demonstrated higher levels of understanding for simpler parameters such as “thermal efficiency” or “energy efficiency” but showed lower levels of understanding for more complex efficiency parameters such as “Hot water production efficiency at rated heat input” or “Annual energy consumption efficiency”.

It is interesting to note that for efficiency parameters, many respondents claimed that they did not understand the parameters, yet they were able to answer the questions correctly. It was logical to associate a higher value of efficiency with better performance, and therefore even respondents who did not think they understood the meaning of the parameter could still make the right choice.

Index parameters

The survey showed that consumer comprehension about index parameters is also low. Index parameters are unit-less values with very complex calculation processes that are not shown on the label. In some cases, a lower index value represents better energy performances, while in other cases it is the opposite. These index parameters evidently carried little meaning to survey respondents, so it was more difficult for them to make educated guesses.

From all of the above data, we are able to draw the following conclusions:

- Simplicity and perhaps familiarity of the parameters appear to be key components for easy comprehension by consumers, evidenced by the fact that physical parameters and simple energy consumption parameters were generally well-understood among consumers.

- Complicated energy consumption parameters and efficiency parameters were both difficult for consumers to understand.

- Index parameters are not expressed in specific units, and therefore it was difficult for consumers to understand them or utilize them in purchasing decisions.

Appliance-using Habits

Appliance ownership in urban families

In order to assess appliance-using habits among Chinese consumers, the project team conducted an appliance ownership survey, including 215 families from six different cities with various family structures and income levels. As shown in Figure 4 below, the results demonstrate that computers (both desktops and laptops), refrigerators, washing machines, and televisions are very popular; all reached or exceeded 100%. Ownership of rice cookers, water heaters, and air conditioners is slightly lower, but still between 80% and 95%.

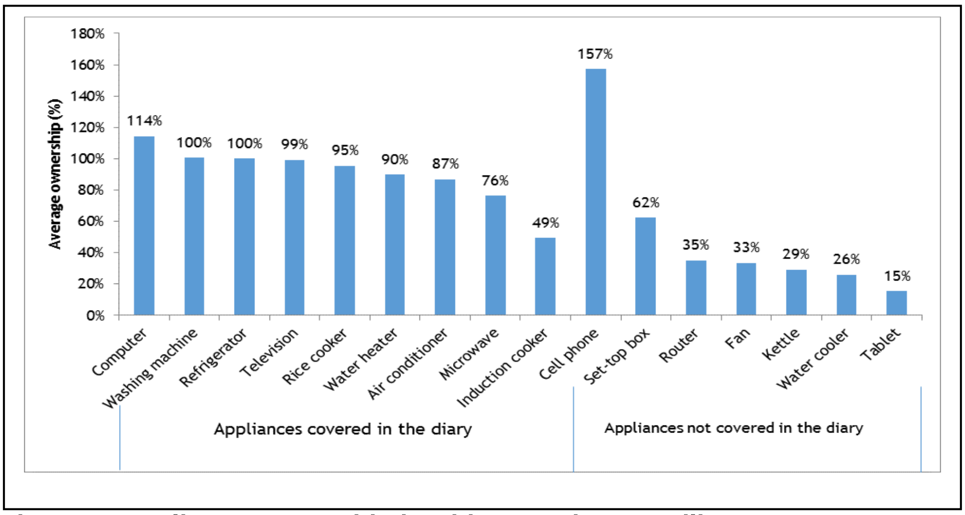


Figure 4: Appliance Ownership in Chinese Urban Families

Gas water heaters were found to be more widely used than electrical water heaters – 52% ownership as opposed to 38% ownership of electrical water heaters. Washing machine ownership is still dominated by top-loading models at 73%, while front-loading machines ownership only reached 28%. Ownerships for desktop computers and laptop computers were 65% and 48%, respectively.

Appliance-using Habits

Participants in this study were asked to record how they use their appliances using a diary designed by the project team. Since the functions of these appliances differ, different parameters were tracked for each. Generally, however, the parameters can be grouped into three categories:

- **Duration or frequency of use**, such as viewing duration for TVs or number of wash loads per week for washing machines.
- **Appliance settings**, such as temperature setting on water heaters or power used by induction cookers.
- **Other habits**, such as whether or not consumers watch TVs with background light and/or unplug them after use

Table 7 summarizes the appliance-using habits of Chinese consumers for the nine types of appliances covered in this study.

Table 7: Appliance-using Habits among Chinese Consumers

Appliance	Parameter	Results
Refrigerators	Refrigerator volume and use	Approximately 2/3 of the total refrigerator volume
	Freezer occupancy	Approximately 2/3 of the total freezer volume
	Number of freezer door	1.8 times per day

	openings	
	Number of refrigerator door openings	4.5 times per day
Washing machines[1]	Number of wash loads	4.1 loads per week
	Cloth occupancy	Approximately 2/3 of the total volume
	Temperature settings (front-load models only)	18 out of the 60 families used warm wash with an average temperature setting of 36º C.
	Unplug after use	64% of families
Televisions	Average viewing duration	4 hours per day
	Unplug after use	66% of families
	Background light	61% medium, 21% strong, 18% weak
	Brightness and contrast adjustment	82% of families used default settings
Water heaters[2]	Average daily use	51 minutes per day
	Only turn on when use? (electrical only)	38% of families only turn on the water heaters when use; 61% of families keep the water heaters on all the time
	Average temperature setting (electrical)	46^{o}C
	Average temperature setting (gas)	43^{o}C
Induction cookers	Average daily use	30 minutes per day
	Average standby duration	90 minutes per day
	Average power used	1400 W
Rice cookers	Average daily use	36 minutes per day
	Average keep-warm duration	14 minutes per day
	Unplug after use	93% of families
	Inner container occupancy	Approximately 50% of the inner container volume (i.e. half load)
Microwaves	Average daily use	5 minutes per day
	Unplug after use	66% of families
Computers3	Average daily use	3.2 hours per day
	Average sleep duration	54% of families used sleep function, averaging 1.1 hours per day
	Average hibernate duration	28% of families used the hibernate function, averaging 4.3 hours per day
	Brightness and contrast adjustment	86% of families used default settings
	Unplug after use	Desktops: 55% of families Laptops: 69% of families
Air conditioners	Average temperature setting	For cooling: 25.5º C For heating: 26.4º C
	Average daily use	For cooling: 5.5 hours per day For heating: 2.8 hours per day

The most notable of the above results are as follows:

- Household washing machines are dominated by top-loading models; only 1/3 of the families owned front-loading machines. However, among those who owned front-loaders, only 30% used warm wash, which uses more energy to heat the water.

[1] This sample included 60 front-load units and 156 top-load 156 units.
[2] This sample included 81 electrical units and 112 gas units.
[3] This sample included 140 desktop unitsand 106 laptop units.

- On average, every family watched 4 hours of TV and spent 3.2 hours using computers daily.
- The majority of families chose to use default settings for brightness and contrast when using computers or TVs. This is significant because these settings affect how much energy the product consumed.
- Following on the above, almost all families chose to watch TV with some level of background light; a majority of families preferred to use medium background light.
- Rice cookers are very popular among Chinese families. Those surveyed used rice cookers once per day, with average duration of 36 minutes. On average, the cookers were filled only half way.
- Microwaves were not very frequently used, with a daily duration of approximately 5 minutes.
- Only 62 families used air conditioners during the study since the study was conducted in October. For both cooling and heating purposes, the temperatures for air conditioners were set at approximately 26°C on average, which is the temperature promoted by the government and environmental protection organizations.[4]

As shown in Figure 5 below, a large proportion of families chose to unplug their appliances after use. A smaller proportion chose to unplug electrical water heaters after use. It is possible that more families chose to not unplug electrical water heaters after use because they wanted to have immediate hot water access, and electrical water heaters require time to heat water to the desired temperature.

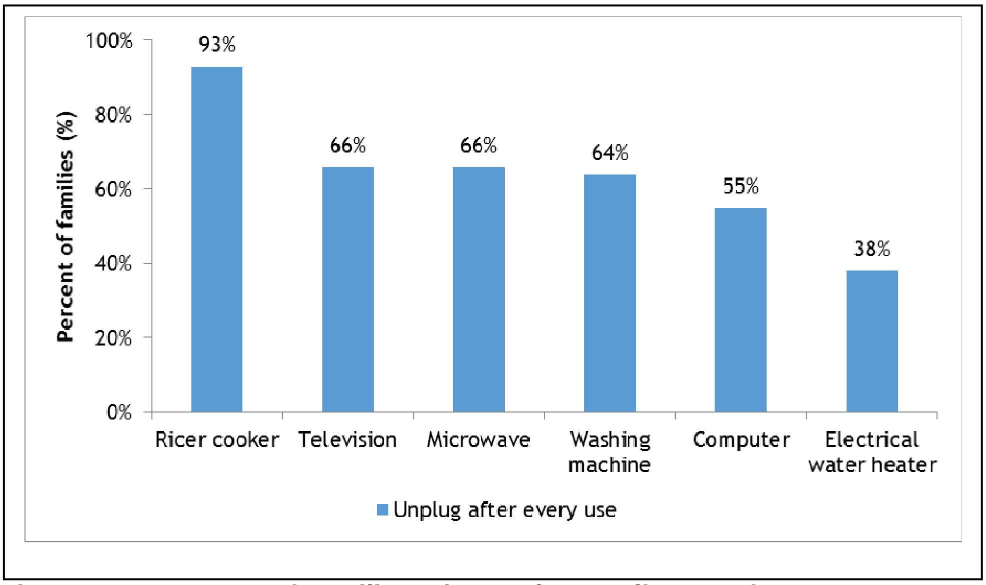


Figure 5: Percentage of Families Who Unplug Appliances after Use

Household electricity consumption

The project team recorded the electric meter readings for each participating family before and after the study. The average electricity consumption during the week was 38 kWh. Therefore, we estimate that average monthly electricity consumption is 163 kWh.[5] This is much lower than in developed

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[4] Decisions on enhancing energy conservation effort, issued by the State Council. (In Chinese). http://www.gov.cn/gongbao/content/2006/content_389909.htm [Date accessed: 2014 Nov. 24]

[5] It should be noted that electricity consumption may vary in different months. This estimation was based on one week of measurement in October.

countries such as the US, where the average residential electricity consumption was over 900 kwh per month in 2012.[6]

Policy Recommendations

Based on our analysis above, we recommend that the Chinese Government focus on revising the aspects of the CEL described below in order to increase consumer comprehension and thereby further promote the purchase of energy efficient appliances.

Improve the readability of parameters

The consumer comprehension survey and interviews demonstrated that technical parameters are the most important aspect of the CEL for consumers; therefore, policymakers should consider improving the readability of technical parameters and make it a top priority so that consumers are able to understand the parameters correctly and make informed decisions when purchasing appliances.

In analyzing consumers' comprehension of 34 technical parameters over nine types of appliances, we observed that simple energy consumption metrics (e.g. input power, standby power, or energy consumption) and physical parameters (e.g. volume, washing capacity) can be easily understood by consumers. Efficiency parameters (e.g. hot water production rate), on the other hand, are more complex and difficult for consumers to understand, and complicated energy consumption parameters (e.g. heating season energy consumption) and index parameters (e.g. 24 hour standby energy loss index) are the most difficult. As such, we recommend that policymakers to use simpler terms on the label design and reduce the technical content of parameters.

Add information regarding consumption and savings to the label

Policymakers may want to consider including information regarding consumption and cost savings on the product labels. Using the data collected in the appliance-using habit diary activity above and appliance power or energy consumption information, we can calculate typical energy consumption for appliances included in the study – such as daily energy consumption, annual energy consumption, or energy consumption per cycle. Energy consumption can then be converted to monetary savings, which is more direct and relevant for the consumers. In addition, the label could reference the most and least efficient models of that product on the market, so that it will be easy for consumers to make comparisons.

Adding the estimated operation cost on the labels could help consumers to visualize the financial benefits of adopting energy efficient appliances. Policymakers may wish to conduct further research to investigate whether adding energy consumption and cost on the label could encourage consumers to choose highly efficient appliances.

Clarify the relationship between energy efficiency tiers and energy consumption

Based on the results of the label comprehension survey described in Section 2, the current China Energy Labels does not clearly communicate the relationship between energy efficiency tiers and energy consumption, which is confusing for some consumers. While many consumers appear to associate higher energy efficiency tiers with lower energy consumption, in some cases survey respondents did not think that a higher efficiency tier indicated lower energy consumption. Therefore, we recommend that a typical energy consumption value for similar products be included as reference on each energy efficiency tier, so that consumers can clearly see the energy consumption differences between different tiers. By providing more direct and intuitive information on the label, it will be easier for consumers to visualize the benefits of choosing a highly efficient appliance that consumes less energy.

Revise energy savings estimates using appliance usage data

Energy savings estimates are typically calculated based on how appliances are being used by consumers in their homes, and the accuracy of this consumer data determines the robustness of the estimates. Historically, very few studies have been done in China regarding consumer appliance

[6] US Energy Information Administration: http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3 [Date accessed: 2014 Oct. 23]

usage habits of consumers; therefore, most estimates of energy savings had to be calculated based on assumptions. This study is the first attempt to bridge the information gap and provide policymakers with real consumer data on appliance usage habits, and policymakers may wish to revise existing energy saving estimates based the data offered here.

Consider appliance usage habits when developing or revising MEPS or test procedures

To effectively push the market towards energy efficient products, MEPS should be designed based on realistic energy savings estimates (as discussed above), and test procedures should be closely aligned with how appliances are used in real-life conditions. In some cases, however, real appliance usage conditions were very different from the conditions set in Chinese MEPS and test standards. For example, the current washing machine test procedure requires models to be tested at full load capacity, but our surveys show that most of families only load their washing machines to two-thirds of the full load. Similarly, the test procedure for TVs requires models to be tested in a dark room, whereas our survey demonstrates that people always watch TV with some background light. For microwaves ovens, the survey shows that 66% of the households unplug the microwave after use; thus, it is questionable whether or not it is necessary to include standby power as part of the MEPS. We therefore recommend that policymakers take appliance usage habits into consideration when developing or revising MEPS and test procedures such that the final policies best reflect how appliances are being used in real-life conditions.

Expanding the usage habits study in future to get even more accurate data

In this study, we investigated the appliance usage habits in 215 households in China. While the results have provided many useful insights, the study was limited by several factors. Firstly, the diary recording method allows significant room for human error. Despite our efforts to train the participants and regularly communicate with them to answer questions, participants may still have made mistakes in their entries. In future studies, individual electric meters could be installed for each appliance to enable accurate and continuous monitoring of the electricity consumption for each household appliance.

Secondly, the sample size in this study was very small, particularly considering China’s large population size. Ideally, surveys should be carried out and replicated in more households in various regions and cities across China to obtain a more complete picture of how appliances are being used.

Thirdly, the diary recording exercise took place in a period of one week in October, and it is very likely that seasonal changes would result in different measurements in the spring or summer. Therefore, we suggest that future study be performed in different seasons of the year to reflect the seasonal variation of appliance usage habits.

Overall, we recommend that policymakers consider repeating and expanding the appliance usage habit study in future to obtain more detailed and accurate data.

What's on? Compliance of Televisions with Energy Labelling and Ecodesign Regulations

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SEVEn

Abstract

The 2014 Evaluation of the Energy Label prioritised the need to address Market Surveillance to recoup the estimated 10% of potential energy savings lost as a consequence of poor enforcement[1]. ComplianTV was initiated to address these needs specifically for televisions (TVs), given the recent entry into force of the TV related regulations and the specific challenges that exist in this market – for example the market size, the breadth of suppliers, the energy impacts and the complexities around the standardisation and measurement process.

ComplianTV supports the market transformation of TVs towards more energy-efficient products. The project works alongside the EU Energy Labelling (1062/2010) and Ecodesign (642/2009) Regulations for TVs in a number of ways: ensuring that non-compliant products are identified and removed from the market, engaging in dialogue with all stakeholders, improving performance through competition and guiding consumers towards the most efficient products available. The project aims to support the activities of national Market Surveillance Authorities (MSAs), existing efforts by industry seeking to adhere to regulations (by increasing knowledge and reducing administrative burdens) and an overall increased culture of compliance among manufacturers and retailers.

So far the project has assessed 172 TV models, identified a number of non-compliant products and created and published the results in a publically accessible database. It has identified standardisation anomalies and produced guidelines for TV testing and recommendations for future policy development; it has inspected the compliance of 100 physical and 100 online shops across 5 countries measuring rates of non-compliant energy labelling (most commonly where a TV does not display the label in a store or omits required information online) respectively and it has established a detailed dialogue with MSAs, manufacturers and retailers across Europe.

The project is delivering an improved compliance rate of future TVs through a detailed discussion and remedy action process with non-compliant manufacturers and retailers, by means of returning to the retailers and checking manufacturer's products to verify the implementation of remedy actions; by

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[1] *Monitoring, Verification and Enforcement Capabilities and Practices for the Implementation of the Ecodesign and Labelling Directives in EU Member States,* CLASP 2011. In CLASP's *Compliance Counts: a Practitioner's Guidebook* (2010) the UK Department for Environment, Food and Rural Affairs noted that: "At present the rate of non-compliance in the UK is estimated to be around 10 to 15% at manufacturing level (failure to meet the claim on the label) and 20% at retail level (absent or incorrect labelling)."

The final report from the Evaluation of the Eco-design Directive was published in 2012 and concluded that *Growing evidence indicates that the level of non-compliance is in the range of 10-20%.* The Intelligent Energy Europe funded "ATLETE" project (2009-2011) found a 20% non-compliance rate following the testing of the Energy Label declarations from a range of domestic refrigerators.

capacity building with European testing laboratories on the TV testing issues and standardisation anomalies uncovered; and national and European workshops with MSAs sharing project outputs.

Introduction

This paper constitutes the main outputs from ComplianTV[2] - an Intelligent Energy Europe funded project running from April 2013 until September 2015. The main project outputs are explained in the proceeding sections: product testing, the online and in-store retail shop inspections, and the various activities to strengthen the community of stakeholders e.g. MSAs, Manufacturers, Retailers, Policy Makers and Consumers.

Energy Labelling and Ecodesign Regulations: Do the TVs comply?

Methodology, Product Selection and Targetting

The project had a target to purchase and test 201 TVs (units) against the technical and information requirements of the Energy Labelling and Ecodesign Regulations for TVs. The testing was divided into 3 batches. Batch 1 constituted 60 models, batch 2, 40 and batch 3, 62 – the remaining 39 models were reserved for step 2 testing whereby 3 additional units are purchased and tested to confirm or otherwise the suspected non-compliance after step 1 testing. Finally, the project tested a 4th batch of 10 models from manufacturers whose products had previously failed testing during the project.

To provide clarity to the market and to consult on due process with the MSAs, it was necessary for the Project to set out and declare how it interpreted certain specific requirements from the Energy Labelling and Ecodesign regulations for TVs and how it would assess the compliance of TVs in general. These were set out and validated in April 2014 within a document called Test Method Interpretations, Tolerances and Communication of Results. As well as providing clarity on the process for step 2 testing, the document also importantly established clear terminology with respect to the term "non-compliant". This simultaneously recognised the importance and position of the MSAs with respect to enforcement, and defined the Project's use of non-compliant as referring to a conformity check performed by the Project against the requirements specified. The interpretation of industry was also strongly taken into account, via consultation and due to the presence of Digital Europe in the project consortium.

A market analysis was conducted based on data from Amazon, a price comparison portal and available market statistics data. Based on the results of the market analysis and online research, a product selection methodology was created. The criteria encompassed technical aspects and economic aspects. Based on the established selection criteria, a list of TVs to be tested was completed and published[3].

The first batch constituted 57 LCD TVs and 3 Plasmas, with a split of 36 A-brand TVs and 24 non-A brands. A-brand manufacturers are defined by the Project as LG, Panasonic, Philips, Samsung, Sony, TCL, Thomson and Toshiba. The screen sizes of the 60 models were split evenly between 4 size groups: <32", 32", 33-42", >42" with models <16" and >55" excluded. The Project was keen to take an intelligence led approach from batch to batch. Therefore, the results of the first batch of testing was used to inform the model selection and targeting approach for batches two and three – in particular the brands included within the sample. The A-brand non-A-brand split evolved in the second and third batches from 36 and 24, to 12 and 28 in batch 2, and 27 and 35 in batch 3. The impact of the batch 3 sample was further enhanced by the use of GfK data depicting which countries the models were sold in: it was the Project's ambition to maximise the reach of the results.

Results

Batch 1

After step 1 testing of batch 1, 43 TVs were declared compliant with the technical requirements with 17 identified as suspected non-compliant. The Project established a dialogue with the respective

[2] www.compliantv.eu
[3] http://www.compliantv.eu/eu/product-testing/product-selection/

manufacturers to provide the test results and if required – to clarify the test procedures. The results regarding the 17 suspected non-compliant cases were further clarified:

- Five models were declared as non-compliant: the non-compliance was accepted after step 1 in the case of four models. One model progressed to step 2 testing, which subsequently failed.
- Six models were declared as compliant: after communication with the manufacturers and in line with the testing procedures, the testing reports were revised. For one specific model, step 2 was initiated and passed.
- The compliance status of six models could not be clarified: five models could not be purchased from the market for retest and whilst three additional units for one model were purchased, on delivery they showed clear signs of use, and were rejected.

In summary, setting aside the six models above, the results of the TVs under test for batch 1 showed:

- 49 (LCD and plasma) models comply with the technical requirements in 642/2009 and 1062/2010.
- 5 TVs were non-compliant in respect to technical requirements in 642/2009 and 1062/2010.

Furthermore, the overall evaluation of the test results revealed the following trend:

- The highest compliance rate came from the two highest price segments (both 100%). The lowest two price segments, <400 Euro and 400-800 Euro, had the lowest compliance rates (73% and 88% respectively).
- Out of the 5 non-compliant cases, one was declared energy class A+, three A and one B.
- The non-compliant cases all originated from non A-brands
- Four models failed the automatic power down (APD) requirement and one model failed the peak luminance ratio (PLR).

Regarding information requirements, 31 models were non-compliant against at least one requirement. 11 manufacturers have since carried out accepted corrective action with 20 cases still open.

Batch 2

As mentioned above, results from batch 1 informed the product selection in batch 2, including a greater proportion of non A-brands. After step 1 testing, 3 models were suspected non-compliant on technical measurements, all due to Automatic Power Down and from non A-brands. Dialogue with manufacturers ensued.

- One manufacturer carried out corrective action which was accepted by the project team. The TV was deemed compliant upon completion of these.
- Two TVs proceeded to step 2 testing; the outcome of this is pending.
- Therefore 38 of the 40 TVs complied with technical requirements in 642/2009 and 1062/2010

Non-compliance on information requirements was initially seen for 24 of the TVs from batch 2. Manufacturers responded to the majority of these cases to agree remedy actions with the project team. The resolution of 17 of these cases remains in progress.

Batch 3

This batch again placed a strong emphasis on testing non A-brands, and also focused on products that declared a high energy rating, brands not yet tested, those with display technologies such as OLED, full/edge LED backlight, multiple tuners, and 3D, and ones that were sold in more than one country to increase the reach of the project. Results were as follows:

- 2 TVs were suspected non-compliant on Peak Luminance Ratio
- There were 6 cases of suspected non-compliance for Automatic Power Down
- 1 TV was suspected as non-compliant for both PLR and APD

Again, all the cases of suspected non-compliance against technical requirements were seen from non-A brand TVs. Dialogue with manufacturers and determination of remedy action remains in progress from this batch, but one TV has moved to step 2 testing.

40 TVs were assessed as non-compliant against various information requirements and subjected to the remedy action process; 11 of these cases have since been resolved.

Batch 4

10 televisions have been tested in batch 4, all from manufacturers of TVs previously tested and suspected non-compliant by the project, but where remedy action was taken by the manufacturer; further testing sought to assess effectiveness of the actions. Testing is now completed and the project team is currently in dialogue with manufacturers; initial findings show one instance of suspected non-compliance on APD and one on both APD and energy label declaration.

Summary

Trends seen from the 162 models tested in batches 1-3 show that cases of suspected and confirmed technical non-compliance were all from non-A brands and all due to Automatic Power Down or Peak Luminance Ratio. By definition, non-A brands are of lower market share and from batches 1-3, 85% of failures were seen from TVs in the lower price bracket of <€400. Beyond this, there were no other significant trends linking the non-compliant models however, such as screen size or display technology. Whilst it is difficult to quantify energy savings lost from non-compliance with these two metrics, these findings have fed into the project's policy recommendations.

A relatively low level of compliance against information requirements was seen in checks of documentation and publically available information accompanying the physical testing. Publically available information was found to be initially non-compliant for 97 of the 162 TVs; the product fiche did not fully comply in around 1 of 3 cases, and just over a quarter of supplied energy labels had a formatting issue.

Regarding remedy action and dialogue with manufacturers, this appeared to be generally effective. Only 17 cases of non-compliance received no response from manufacturers and had to be referred directly to MSAs. Resolution of the last open cases are intended to be completed by the end of the project in September 2015.

Where the project moved to step 2 technical testing, some issues were seen with availability of models due to the relatively short shelf life of TVs. 10 compliant models were unable to be sourced for follow-up testing despite best endeavours, removing the ability to fully resolve these cases.

Consumer Eye View: Inspecting TVs In-store and Online

Methodology

The objective of this exercise was to check a sample of retailers across 5 Member States to understand their level of compliance with the display and proper use of the energy label. The inspections were divided into two rounds. For each round, each partner visited 20 stores. The second round constituted a repeat inspection of all stores from the first round, after a discussion period about the findings and implementation of the agreed remedy actions with the retailers involved. Project partners from France, Germany, Austria and the Czech Republic all delivered 20 in-store and 20 online inspections, with the UK partner conducting a further 20 in-store inspections and the Belgium partner 20 online inspections: totalling 200 inspections – 100 each for in-store and online.

For the in-store inspections, retailers were divided into 4 categories: electronic superstores, department stores, supermarkets and electronic specialists / independents. Each national partner was allowed to use local intelligence and national priorities in selecting what proportion of each store type made up the sample of 20 and their geographical location – with the exception that at least 2 of the stores visited be electronic superstores and a minimum of 12 of the stores in the sample be drawn from the other 3 store types. Labels should conform entirely to the format specified in Annex V of EC regulation 1062/2010[4] and be placed on the front of the TV, clearly visible. Instances of non-compliance were characterised into 4 classifications: placement issues when the label was either hidden or otherwise obstructed from view, format issues when the label was graphically amended, in the wrong colour, size or otherwise not following the regulated format, application issues when the label did not match the model it was affixed too, or otherwise missing in its entirety.

For the in-store inspections, data was collated for both un-boxed and boxed TVs. All boxed TVs at the point of sale are required to display an energy label in the same way that unboxed ones are. In terms of classification of non-compliance, where there are a number of unlabeled boxed TVs, if one model is un-boxed and fully labelled, all of the related boxed TVs with the same model number were recorded as correctly labelled. Where there is an unboxed TV price marked but without an Energy Label (or even if there is no example unboxed, but still priced and individual boxes do not bear the label), all the associated boxed TVs of that same model are considered non-compliant according to 1062/2010. Data was collated at both the individual unit level and at the model level, where many units of the same model were for sale – such as can be the case for boxed TVs. ComplianTV used the 'model' level comparison for comparing and reporting data from rounds 1 and 2.

For the online inspections, retailers were selected by the national partners with central organisation and communication so as not to duplicate on international retailers. For each store, 20 TVs were selected, drawn from a stratified random sample which specified an equal share across 4 different screen size groups and proportional mix of brands. In order to be considered correctly labelled at the time of the inspection, if the seller was not displaying the Energy Label, TVs needed to display the following 4 pieces of energy related information, in this specified order, according to Annex VI of EC regulation 1062/2010:

1. Energy efficiency class
2. On-mode power consumption
3. Annual power consumption
4. Visible display size

Instances of non-compliance were characterised into 3 classifications: format issues, where the energy related information was not displayed in the right order or some information was missing, the displayed label did not fit the colour, or the format which is required from the regulation; application issues where the label did not match the model; or otherwise the TV was missing the label and the energy related information altogether.

Experiences In-store

Results Round 1

Consumers on average are likely to find energy labels missing on 3 out of every 10 models sold[5]. With a sample size of over 5,000 TVs the non-compliance rate was 32% (at the individual model level). When considering each unit of a TV present, non-compliance was measured at 41%, increased by instances of multiple non-compliant boxed TV units of the same model present in larger stores. Out of the 100 stores inspected, nearly half were electronic specialists, with the remainder being electronic superstores, department stores and supermarkets. On average, superstores had the highest level of compliance and supermarkets the lowest. The predominant reason for non-conformities was TVs missing the energy label (84%) followed by formatting issues on 10%. There was anecdotal evidence of a low level of engagement in labelling by some retailers (particularly smaller independents), some of whom were simply not aware of their responsibilities to ensure

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[4] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2010:314:0064:0080:EN:PDF

[5] http://www.compliantv.eu/eu/energy-label-display/monitoring-in-the-stores/

labelling at the point of sale. Consumers are believed to broadly understand the energy label[6] but its omission at the point of sale dramatically reduces the chance of energy efficiency being a factor in the purchasing decision.

Geographically, you were most likely to find the highest proportion of compliant TVs on sale in Germany (82%) and least likely in the UK and France (57%). Electronic superstores had the highest average level of compliance (76%) with supermarkets the lowest (53%).

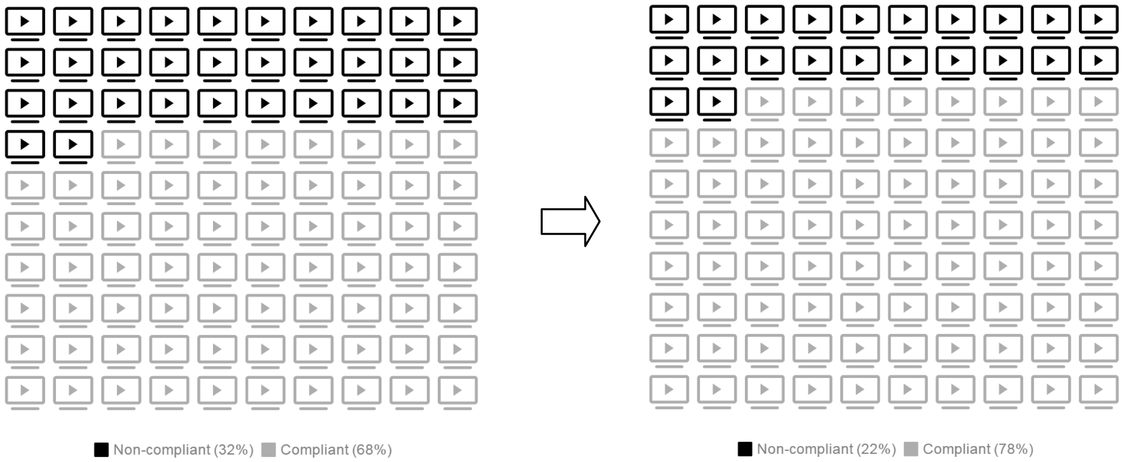

Figure 1 – Non-compliant TVs in-store. In round 1 conducted at the end of 2013, 32% of TVs were found non-compliant (using the model level assessment) in 100 stores across 5 countries (n=5,128) – this decreased to 22% in round 2 (n=5,398).

Boxed TVs

The issue of non-compliance was more prominent for boxed TVs, where 46% seen were non-compliant, as opposed to un-boxed TVs where this number was 30% (according to the model level assessment). Out of all the non-compliances seen at unit level, boxed TVs represented 40% despite only representing 21% of the total sample size. Most of the boxed TV units inspected were found in the electronic superstores (62%), followed by the supermarkets (20%).

6 http://www.clasponline.org/Resources/Resources/StandardsLabelingResourceLibrary/2013/~/media/Files/SLDocuments/2013/2013_05_EU-Energy-Labelling-Comprehension-Study.pdf

Figure 2 – Non-compliant boxed TVs. With no example model labelled; all TVs were counted non-compliant

Results Round 2

Round 2 saw the project team again check display of the energy label on over 5,000 TV models in 100 stores, 86 of which were visited in round 1. After round 1, the project team communicated results with retailers and gave guidance on improving the situation where compliance was low. The result was an overall improvement - comparing both rounds at the 'model' level, an increase in compliance of 10 percentage points was seen. 61 of the 86 stores revisited (14 stores had closed down since round 1) improved the level of correct labelling, and a significant increase in stores achieving over 80% compliance was seen; 48 stores reached this level in round 2 compared with 25 in round 1.

Geographically, compliance was seen to be higher in the Czech Republic (89%) and Germany (88%) than in the UK (74%) and France (70%). Supermarkets again saw the lowest compliance and electronic superstores the highest in round 2, but this improved to 66% and 84% respectively.

Remedy Actions

The project team continued communication with retailers after round 2 and requested further remedy actions where necessary. There were several positive examples where retailers communicated extensively with the project to improve procedures on labelling, knowledge of the regulations and access to labels when not initially provided by the manufacturer between rounds. Specifically these included an electronic specialist in the Czech Republic which increased compliance from 13% to 100% and a large UK department store improved compliance across three of its stores by an average of 23%, with all three achieving compliance of over 82% in round 2.

Summary

Overall, energy labelling of TVs in stores is improving, as retailers become more familiar with their responsibilities. The figure of 78% compliance in round 2 (at the 'model' level) builds on the score of 68% in round 1. Compliant labelling of unboxed display TVs, typically an action performed by the retailer was seen to improve to 80% in round 2 (from 70% in round 1).

Some issues remain with the labelling of boxed TVs, particularly in electronic superstores and supermarkets; while compliance improved by 11 percentage points in round 2, still around 1 in every 3 boxed TV models was non-compliant, most often as a result of a missing label. Some label formatting issues were seen in round 2, which were addressed in round 1 communications, but may have been due to older stock running through the supply chain. The project produced guidance materials on labelling for retailers and understanding the energy label for consumers which were disseminated widely as part of round 2 communication.

Experiences Online

Results Round 1

In summary, out of a total of 2,002 TVs inspected there was a 74% non-compliance rate regarding the display of Energy Labels on TVs. Over 80% of the non-compliant cases were due to formatting errors – in this context (prior to the change in regulations for online retailers from January 2015) this is where some of the required energy information to be displayed is either missing or presented in the wrong order to the consumer. This picture varied country by country, with Germany having a 53% non-compliance rate and the Czech Republic a 95% non-compliance rate.

Results Round 2

Round 2 saw a further 1,982 TVs checked online, following the change in legislation from January 2015 requiring online retailers to display the energy label and product fiche in listings for new products placed on the market. As the date products entered the market could not always be ascertained, application of the appropriate form of the regulation was not always possible, but the project team was able to assess whether a product did not comply against either iteration of the regulation.

68% of products checked were assessed as non-compliant. Again this varied by country; none of the TVs checked in the Czech Republic achieved full compliance whereas German online retailers scored the highest rate of compliance at 60%.

Remedy Actions

Communication of results to retailers from round 2 and establishing remedy action is currently in progress.

Summary

Results suggest a small (6%) improvement measured in a period of around a year, and the timing of the checks allows assessment of whether the change in regulations for online retailers has made achieving compliance easier. Review of screenshots suggest around two-thirds of the 100 retailers checked have made at least some attempt to present listings in a form compliant with the new regulations, 8 months after coming into force. It is hoped that the new legislation will ease the administrative burden for retailers, point consumers toward product energy data and standardize information for easier comparison.

Is Labelling Compliance Improving In-store?

Retailers' compliance with requirements specified in the Regulation has been assessed in a number of studies and projects, carried out by both MSAs and civil society organisations. Data from ComplianTV suggests that TV retailer labelling compliance has seen a fairly rapid increase, and is currently levelling out between 60-85%. Several projects have shown variations between different types of retailers in their labelling compliance. ComplianTV saw variation in the compliance rates of physical stores when assessing compliance by 'model' (68% compliance when counting each different product as one compliance or non-compliance, the figure used below) and 'unit' (59% compliance when counting multiple units for sale as multiple compliance or non-compliance). It should be noted that the methodology for the projects and studies referenced were not identical in each case, for example it is not known if previous studies incorporated 'unit' or 'model' level sampling. Whilst the 'unit' level more closely follows the letter of the Directive and is the approach generally used by MSAs, ComplianTV focused its reporting on the 'model' level, as this is a considered to give a more representative picture of a store's compliance; where large numbers of boxed TVs are unlabeled, results can potentially be negatively skewed, and correction of a large amount of non-compliance of this type can be achieved relatively easily when the store is aware of their responsibilities on boxed TVs.

Table 1 – Comparison of Retailer TV Labelling Compliance across studies 2012-2014

Year	Activity	Compliance Rate
2012	National Measurement Office Compliance Project	13%
2013	Come on Labels	63%
2013	German National Survey	76%
2013	Italian National Survey	85%
2014	MarketWatch round 1	70%
2014	ComplianTV round 1	68%
2015	MarketWatch round 1	63%
2015	ComplianTV round 1	78%

Sources: Energy Labelling Framework Directive: UK Compliance Project 2012; Background report I: Literature review – Evaluation of the Energy Labelling Directive and specific aspects of the Ecodesign Directive; http://www.come-on-labels.eu/displaying-energy-labels/status-of-appliance-labelling; http://www.market-watch.eu/shops

Compared with other product categories, TVs currently show compliance rates below some white goods but show a significantly higher compliance rate compared to those of wine storage appliances and air conditioners (subject to labelling regulations in 2010 and 2011 respectively).

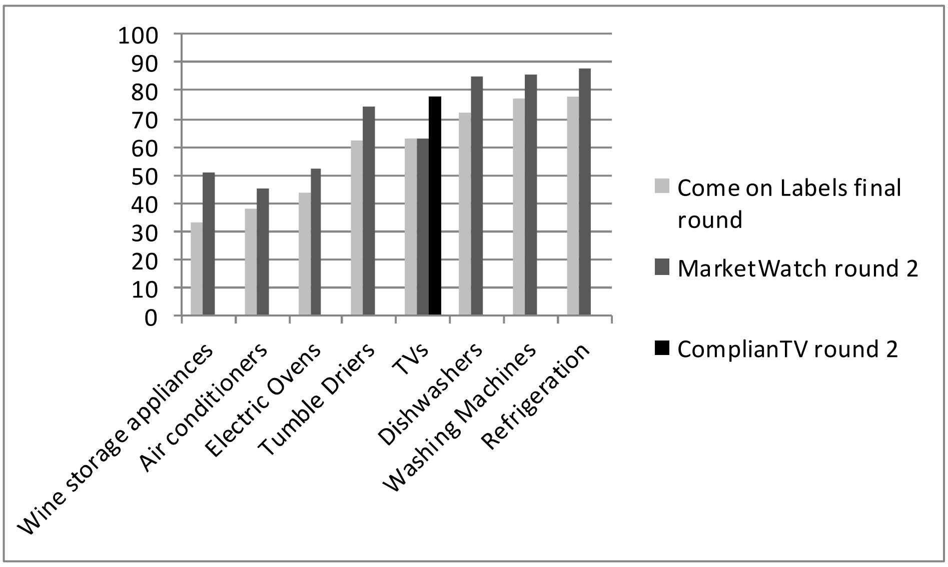

Figure 3 - Studies of labelling compliance rates of multiple product groups including TVs Data is from physical shops only.

Strengthening the Community: Sharing Project Outputs

The outputs of the project are designed to either empower and / or strengthen those actors, stakeholders and audiences that are involved in the TV market – whether they are the makers, the sellers, the purchasers or those that set policy for them, test them or enforce their laws and regulations. The table below highlights how the many project's outputs serve to help these wide and varied audiences.

Table 2 – How ComplianTV project outputs get shared with stakeholders and audiences

	MSAs	**Manufacturers**	**Retailers**	**Laboratories**	**Policy Makers**	**Consumers**
Product Database	☑	☑		☑	☑	☑
Workshops	☑	☑	☑	☑	☑	
Guidelines	☑	☑	☑	☑	☑	
Test Report Template	☑	☑		☑		
Policy Recommendations	☑	☑	☑	☑	☑	
Consumer Leaflets			☑			☑

Product Database

The main objective for the database is to make the data from product testing available to MSAs and other relevant stakeholders. In order to allow a quick overview of the tested TV models, the front page of the database displays the overall compliance as well as the energy efficiency class, both declared (by the manufacturer) and measured (by the laboratory). Then, for each model, there is the possibility to have several further testing criteria displayed in individual factsheets. The goal was to develop an online tool, which was both informative and succinctly arranged.

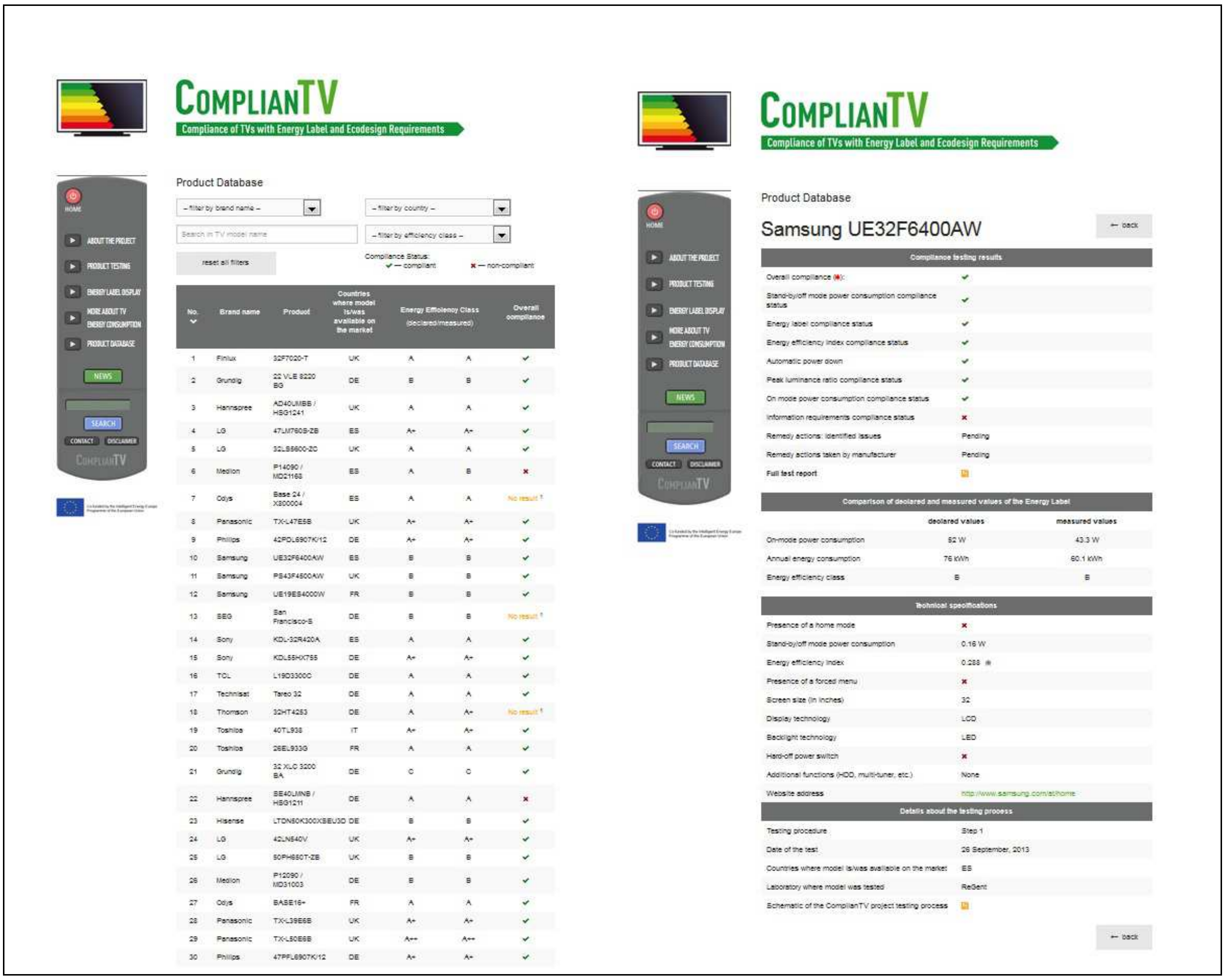

Figure 4 – Screen shots from the ComplianTV online product database showing 1) the summary view and 2) the model view source: www.compliantv.eu/eu/product-database

Test Report Template

Similar to other civil society led market surveillance projects, ComplianTV has utilised the skills and experience within the consortium to draft, refine, test and implement a product test reporting template – for the benefit primarily of laboratories and MSAs. But unlike other projects, ComplianTV will publish the test report template (in its final version) for the benefit of those who would save time and money in utilising it, including European laboratories external to the Project team.

Guidelines & Leaflets

Various sets of guidelines and leaflets have been produced by the project to serve the TV community; they include:

- Guidelines for Product Testing
- Guidelines for Conducting In-store and Online Shop Inspections
- Brochures on How to Display Energy Labels in Store and Online
- Consumer Leaflet on Understanding the Energy Label

Workshops

The production of guidelines is supplemented by the action of hosting national and international workshops across a range of topics including the preparation, delivery and evaluation of in-store and online shop inspections, the outputs of the project in general and more specifically, the experience from the compliance testing of products - explained further in the proceeding section.

Reviewing the Regulations: How Can They Be Improved?

With the combined expertise of three testing and certification laboratories - VDE, IPI and Re/genT – and the oversight of the Technical University of Berlin, and with the benefit of testing and verifying over 160 models of TV, the Project was able to learn and understand a considerable amount about the European regulations used to implement standards and verify conformity. What follows is the observations and recommendations for improving the current suite of Ecodesign 642/2009 and Energy Labelling 1062/2010 regulations, which have been provided to the policy makers.

On-mode Power Consumption

Volume Setting

The testing programme identified and concluded that the volume setting of the TV can have an impact on the measured power consumption. Specifically, that setting the speak volume to a lower level can result in considerably lower power consumption. Currently, the test standards do not set a standard requirement for the volume setting when models are under test.

The Dynamic Broadcast content

During the testing programme a different power consumption curve was measured in response to the "Dynamic Broadcast Content". This was a new behaviour for on-mode power consumption, not previously experienced by the laboratory testing team.

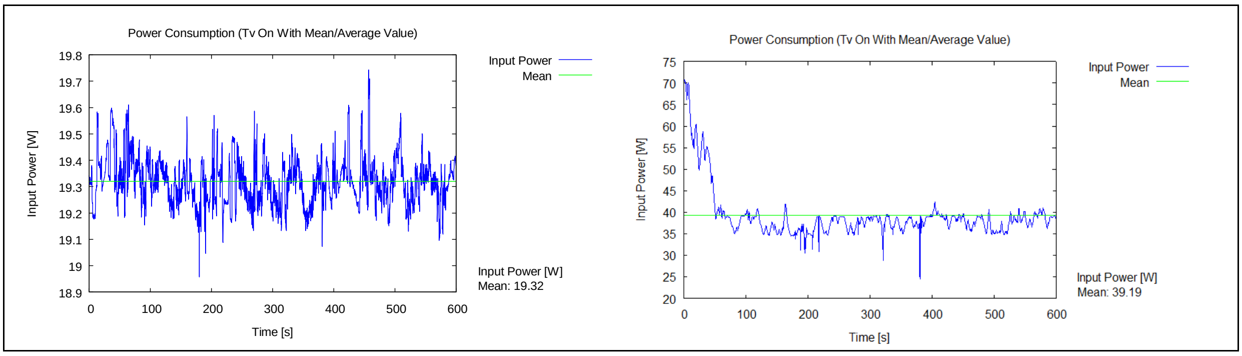

Figure 5 – Input power consumption over time for a TV: on the left with no dynamic power variation and on the right with special dynamic power variation.

Automatic Power down

The testing programme identified that there was a lack of a measurement tolerance for the verification of the 4hr automatic power down requirement within the ecodesign TV Regulation and furthermore that it was unclear whether or not the TV had to complete the power down process within the 4hrs or to have started it.

Peak Luminance Ratio

The experience from testing over 160 individual models demonstrated the complexity of verifying TV performance against this requirement. On account of the flexibility provided for in the regulation, the lack of a defined unified test pattern makes the independent testing and verification process longer and more costly: complicating the issue for MSAs and laboratories.

EEI and annual power consumption

For the calculation of the EEI and the annual on-mode energy consumption, the Energy Label Regulation 1062/2010 defines the calculation formula, where P_{basic} depends on the number of tuners in the TV. However, there is no explicit definition or explanation in the Regulation (e.g. whether it is based on hardware or on functionality).

The Energy Label also states that “the luminance of the television in the home-mode or the on-mode condition as set by the supplier, is automatically reduced between an ambient light intensity of at least 20 lux and 0 lux”. This requirement creates a grey area because any reduction of the power consumption between any light intensity of at least 20 lux, and 0 lux, will make a television compliant. In a testing perspective, ComplianTV recommended, if such a requirement is maintained, that the levels of the light intensity should be set more precisely, and the required power consumption reduction should be quantified.

Conclusions

Overall findings of the project show examples of both good and poor compliance against the various requirements in the Energy Labelling and Ecodesign Directives for TVs. Implementation by the market has been seen to be effective against many of the technical performance requirements, with the majority of TVs measured as compliant against their declarations of energy efficiency, standby power and on-mode power.

Through the large volume of the project’s testing program, a number of useful trends and insights have been uncovered. These include the several cases of non-compliance against automatic power down and peak luminance requirements, and the concentration of this among cheaper TVs and non-A brand; the correlation between volume level and power consumption and the behavior of a TV’s power consumption in response to the Dynamic Broadcast Content. The testing of 172 TV models has enabled a significant transfer of information on testing best practice and enabled harmonized approaches between laboratories providing a strong evidence base for areas of focus in the upcoming revision of ErP regulations for TVs and the policy recommendations detailed above.

However, compliance against information requirements in the Directives was seen to be low, and there remains significant scope for improvement in the provision of this to consumers, particularly by online retailers. Manufacturers and retailers on the whole did co-operate with the project and often undertook remedy actions where necessary, and improvement was seen in retailers’ energy labelling compliance during the project. Comparing the improvement in the provision of energy information with that of the market share of TVs in the higher energy classes will remain an important metric to determine the effectiveness of this aspect of the regulation addressing consumer education on energy using products.

Further improvement in this area is essential for a product category such as TVs, where performance and features are often the primary factor in a purchasing decision ahead of energy efficiency, to bolster the energy saving potential of the Directives. Therefore this remains an aspect of Ecodesign and Energy Labelling policy that still has potential as a tool to drive market transformation towards TVs of the higher energy classes.

However, ComplianTV’s extensive picture of the market provides further useful guidance on whether information requirements and their provision should be revised and how this could best align with the Commission’s recent proposal of a database for energy-related products.

Energy efficiency standards and labelling in Latin America – the issue of alignment and harmonisation

Wolfgang F. Lutz

Energy Strategies for Sustainable Development

Abstract

Following early programmes in Brazil (since 1984) and Mexico (since 1992), energy efficiency standards and labelling schemes have been implemented in most countries of Latin America. Despite of several efforts over the past decades to create harmonised standards and labelling schemes, Latin America presents a heterogeneous picture, with major differences between Mexico and Central America on the one side and South America on the other. Yet, also within the South American sub-region many smaller, yet important, differences between the schemes of individual countries exist. These differences, which indicate a lack of coordination among the efforts of each country, are not conducive to regional, or even sub-regional harmonisation. The purpose of this paper is to shed light on this reality, by addressing the following issues: First, an overview on energy efficiency standards and labelling programmes will be given, focussing on Brazil, Mexico and other countries in the Southern Cone and Andean sub-regions. For each national programme, measurement standards, labelling standards and regulations, and MEPS will be addressed. Second, the degree of alignment of the various national schemes with international and other reference standards; regional labelling schemes, like European Union regulations, the US standards and labelling programme and other national programmes in the Region, and the status of MEPS will be addressed. Third, the findings will be discussed with regard to several aspects, including the technical quality of the standards and regulations, the process and methodology of establishing them and the level of ambition, and conclusions will be presented. The paper builds on two decades of involvement of the author in EE S&L programmes in Latin America, as well as recent research.

1 Introduction

Although energy efficiency policies and programmes have been conceived in Latin America since the 1980ties and gained some momentum in the 1990ties, it is only since the turn of the millennium that they are perceived as alternatives, or at least complements, to the traditionally supply-side oriented energy policies in the Region. This shift is related to the changes of economic and environmental policies, which Latin American nations have undergone over the past decades, and which have been widely influenced by the changing paradigms of international financial institutions (IFIs) like the World Bank, the International Monetary Fund (IMF) and the Inter-American Development Bank (IDB). During the decade of the 1980ties, energy sector policies were characterised by expansion of energy supply and infrastructure, under the egis of IFIs and state-owned, vertically integrated public utilities. It were the same IFIs who, following the prescriptions of the "Washington Consensus" induced Latin American governments to deregulate their energy markets and to unbundle and privatise their energy companies. Since the first decade of the new millennium renewable energy and energy efficiency are on the rise, albeit with notable differences in the ambition and the effectiveness of the policies and programmes implemented in individual countries. Interesting enough, the two largest countries of Latin America, Mexico and Brazil, who have refrained from or have only cautiously implemented neoliberal reforms, were the pioneers in the development and implementation of energy efficiency programmes in Latin America. Brazil's PROCEL[1] programme started already in 1984, while Mexico established its National Commission for Energy Saving (CONAE[2]) and related programmes in 1989. Currently, almost all Latin

[1] *Programa Nacional de Conservação de Energia* (PROCEL).
[2] *Comisión Nacional para el Ahorro de Energía*, since 2009: *Comisión Nacional para el Uso Eficiente de la Energía* (CONUEE).

American countries are engaged in some kind of energy efficiency activity, which widely vary in maturity, ambition and effectiveness [1], [2].

From the very beginning, energy efficiency standards & labelling have assumed a prominent place in the Region's energy efficiency programmes. Pioneers have again been Brazil and Mexico, whose energy efficiency programmes started with a major focus on energy efficiency standards & labelling. Since the turn of the millennium, other countries have followed, notably Argentina, Chile, Uruguay and several countries of the Andean and Central American regions. Currently, almost all countries of Latin America have implemented, or at least initiated, an energy efficiency standards and labelling programme.

Due to the lack of effective economic integration in Latin America, energy efficiency standards & labelling programmes are national and not necessarily harmonised with each other, although most of the programmes are at least partly aligned with standards & labelling schemes in other parts of the world. The purpose of this paper is to explore the characteristics of each of the major standards & labelling programmes in the Region and to compare these characteristics among each other and with those international schemes that have served as reference for national policy makers, notably the standards & labelling schemes of the European Union and of the United States and Canada.

2 Subject matter and scope

Energy efficiency standards & labelling schemes are currently implemented in more than 80 countries world-wide.[3] As will be shown below, most countries of Latin America have also implemented or are at least in the process of implementing such schemes. Both energy labelling and minimum energy performance standards are recognised as very cost-effective instruments to reduce the energy consumption in the residential, commercial, industrial and transport sector, focusing on energy consuming and energy related products like household appliances, lamps and luminaires, consumer electronics, building elements, electric motors and other industrial equipment, cars, etc.

In order to be viable and effective, energy efficiency standards & labelling programmes need to include the following main elements: (i) measurement standards (test procedures), in order to establish the performance of the product in an objective and reproducible manner; (ii) an energy label which provides veracious and reliable information to consumers, and (iii) minimum energy performance standards (MEPS), i.e. binding energy efficiency thresholds for the placing of products on the market. Yet, to make a programme work, these basic elements need to be sustained by a system of procedures and physical infrastructure, including certification and accreditation procedures, test laboratories, monitoring and verification of the programme and market surveillance. In order to make energy labelling and minimum energy performance standards mandatory, legal acts need to be issued by the authority.

The focus of this paper will be on measurement standards (test procedures), "labelling standards" and regulations for mandatory energy labelling and minimum energy performances standards (MEPS). Measurement standards are usually issued by national standardisation organisations and may be fully or partially aligned with international, regional or other national standards. In several Latin American countries the national standardisation institute also issues so-called "labelling standards", which define the design and other characteristics of the energy label. Regulations for mandatory energy labelling and MEPS are subject to national legislation of each country.

Despite of several efforts over the past decades to create harmonised standards and labelling schemes in the Region, notably the elaboration of regional labelling standards by the Pan American Standards Commission COPANT[4], Latin America presents a heterogeneous picture, with major differences between Mexico and Central America on the one side and South America on the other. Yet, also within the South American sub-region many smaller,

[3] See e.g. www.clasponline.org

[4] Comisión Panamericana de Normas Técnicas / Comissão Panamericana de Normas Técnicas / Pan American Standards Commission (COPANT).

yet important, differences between the schemes of individual countries exist. These differences, which indicate a lack of coordination among the efforts of each country, are not conducive to regional, or even sub-regional, harmonisation.

The purpose of this paper is to shed light on this reality, by addressing the following issues: In Section 3, an overview on energy efficiency standards and labelling programmes will be given, focussing on "mainstream" developments in Brazil, Mexico and other countries in the "Southern Cone" ("*Cono Sur*") and Andean sub-regions. For each national programme, measurement standards, "energy labelling standards" and labelling regulations, and MEPS will be addressed. In Section 4, the degree of alignment of the various national schemes with international and other reference standards; regional labelling schemes, like European Union regulations, the US standards and labelling programme and other national programmes in the Region, and the status of MEPS will be addressed. In Section 5, the findings will be discussed with regard to several aspects, including the technical quality of the standards and regulations, the process of establishing them and the level of ambition. Finally, in Section 6, past and current international initiatives to foster alignment and harmonisation of EE S&L programmes in Latin America will be briefly addressed and conclusions will be presented, which may be taken in consideration by policy makers in Latin America and the international standards and labelling community, in order to improve national schemes and achieve higher degrees of alignment and harmonisation.

3 Energy efficiency standards and labelling programmes in Latin America

3.1 Brazil

The Brazilian energy efficiency labelling programme PBE[5] was established in 1984, by agreement among the Ministry of Industry and Commerce, the Brazilian Electric and Electronics Industry Association (ABINEE) and the Ministry of Mines and Energy. The programme is coordinated by the National Institute of Metrology, Standardisation and Industrial Quality (INMETRO)[6], with the participation of manufacturers. Initially voluntary, the labelling is currently mandatory for 27 products, of a total of 32 energy-using and energy-related products included in the programme, including several household appliances, lamps, air conditioners, fans, water heaters, televisions, renewable energy systems and equipment, computers and peripherals, stoves and ovens, electric motors, pumps, distribution transformers and car tyres, among others (Table 1).[7] Labelling regulations are currently promulgated by Decree (*Portaria*) of the President of INMETRO.[8] The Brazilian energy label is similar to the EU label, with some differences, notably with regard to the number of energy efficiency classes and some design features. Some design features of the Brazilian label were recently revised.

Since 1993, the National Energy Conservation Programme PROCEL[9] and the National Programme for the Rational Use of Petroleum Derivatives and Natural Gas CONPET[10] offer endorsement labels for products with the best energy efficiency levels within certain product categories (*Selo PROCEL* and *Selo CONPET*). Products eligible for *Selo PROCEL* typically have to comply with energy class "A" and additional requirements, like maximum annual energy consumption or other environmental criteria, according to the respective regulations published by PROCEL.

The Brazilian Energy Efficiency Law of 2001[11] confers to the government the authority and responsibility to establish mandatory minimum energy performance standards (MEPS) for

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[5] *Programa Brasileiro de Etiquetagem* (PBE)
[6] INMETRO is an autonomous body of the Ministry of Development, Industry and Foreign Trade, established in 1973.
[7] Voluntary labelling regulations also exist for residential, public, commercial and services buildings and for certain types of motor vehicles.
[8] Previously, the Decrees referred to *Regulamentos Específicos para Uso da Etiqueta Nacional de Conservaçao de Energía* - ENCE, which still exist for some products.
[9] *Programa Nacional de Conservação de Energia* (PROCEL).
[10] *Programa Nacional de Uso Racional dos Derivados do Petróleo e do Gás Natural* (CONPET).
[11] *Lei de Eficiência Energética Nº 10.295/2001.*

energy using products. The process of standard setting follows established procedures which include public hearings and consultations, and is led by a Committee[12] which is composed of several ministries, the regulatory agencies for electricity (ANEEL) and petroleum and gas (ANP), a representative of academia and an independent expert. MEPS are promulgated by Inter-ministerial Decree (*Portaria Interministerial*) of the Ministries of Mines and Energy, Science and Technology, and of Development, Industry and Foreign Trade.

So far, MEPS have been established for the following products[13]:

- Three-phase electric motors (2002 and 2005)
- Compact fluorescent lamps (2006 and 2010)
- Household refrigerators and freezers (2007 and 2011)
- Air conditioners (2007 and 2011)
- Gas stoves and ovens (2007 and 2011)
- Instantaneous and storage gas water heaters (2008 and 2011)
- Incandescent lamps (2010)
- Electromagnetic ballasts for high pressure sodium vapour and metal halide lamps (2010)

The Inter-ministerial Decrees refer to "Specific regulations establishing the maximum levels of consumption" and to "Programmes of Objectives" ("*Programas de Meta*"), which establish i.a. the periods of review of the thresholds defined (which is usually every four years).

3.2 Mexico

The Mexican system of energy efficiency standardisation was initiated in 1992, based on the Federal Law of Metrology and Standardization[14]. Based on the work of former CONAE[15] and of the National Advisory Committee for Official Mexican Energy Efficiency Standards[16], the first standards were implemented in 1995. Mexican energy efficiency standards are Official Mexican Standards (*Normas Oficiales Mexicanas* – NOM), which – in accordance with the Federal Law of Metrology and Standardisation – are mandatory. The Official Energy Efficiency Standards are denominated "NOM-ENER" and include – in one legal document – test procedures, minimum energy efficiency standards and labelling requirements. The Mexican energy label follows the model of the US Energy Guide, including a continuous scale which indicates the relative savings of the product with regard to the threshold defined by the NOM. Test procedures and MEPS are partly aligned with US rulemaking. NOM-ENER are promulgated by the National Consultative Committee of Standardisation for the Preservation and Rational Use of Energy Resources[17], which is presided by the General Director of CONUEE, following a transparent and participatory process, involving stakeholders.

Currently, 29 NOM-ENER are in force, including standards for household appliances, air conditioners, water heaters, lamps, lighting systems, electric motors, pumps and pumping systems, distribution transformers, commercial refrigeration appliances, mechanised tortilla machines, the building envelope of residential and non-residential buildings, thermal insulation material for buildings, glass and glazing systems for buildings, industrial thermal insulation, standby electric power of equipment and appliances, as well as CO_2 emissions and fuel efficiency of automobiles (Table 2). The NOM for compact fluorescent lamps, room air conditioners and commercial refrigeration appliances were jointly promulgated by CCNNPURRE and the National Consultative Committee of Consumer Safety, Commercial

[12] *Comitê Gestor de Indicadores e Níveis de Eficiência Energética* (CGIEE).
[13] In brackets: years of first promulgation and recast of the respective regulation.
[14] *Ley Federal de Metrología y Normalización*
[15] *Comisión Nacional de Ahorro de Energía* (CONAE), since 2008: *Comisión Nacional de Uso Eficiente de la Energía* (CONUEE)
[16] *Comité Consultivo Nacional para las Normas Oficiales Mexicanas de Eficiencia Energética*
[17] *Comité Consultivo Nacional de Normalización para la Preservación y Uso Racional de los Recursos Energéticos* (CCNNPURRE)

Information and Practices[18]. In the case of CO_2 emissions and fuel efficiency standards of automobiles, the Ministry of the Environment and Natural Resources[19] is the leading entity.

In addition to CONUEE's mandatory standards and labelling programme, the Electric Power Saving Trust Fund (FIDE)[20] offers the possibility to manufacturers to acquire an endorsement label (*Sello FIDE*) for equipment that exceeds the minimum energy efficiency level defined by the NOM. FIDE has established technical specifications for a wide range of products.

3.3 Other countries of the Region

While Brazil and Mexico have pioneered energy efficiency standards and labelling in the Region, other countries have followed since the 1990ties, yet with different degrees of ambition and rigour. Early examples are the development of test procedures and labelling standards in Colombia, Peru and Venezuela [3], as well as mandatory energy labelling in Costa Rica, following the Law on Regulation of the Rational Use of Energy of 1994[21]. These early initiatives were followed by programmes in Argentina, Chile and Uruguay. More recently, also Bolivia, Ecuador, Paraguay and more Central American countries have initiated energy labelling activities. Some of the countries mentioned are in the process of revising or updating their energy labelling standards and regulations or are in the process of introducing MEPS.

A specific feature of the energy efficiency standards and labelling programmes in several Latin American countries are standards issued by the respective national standardisation institute which define, i.a., the energy label design, the efficiency classes and the underlying metrics. These standards, which are referred to in this paper as "(energy) labelling standards" are voluntary standards. In order to make them mandatory, a separate legal act is required, such as a government resolution or administrative order (like in Argentina and Chile) or a technical regulation (like in Peru). The "labelling standards" usually refer to test procedures or measurement standards, which are separate standards, issued by the national standardisation institute.

3.3.1 Andean Region

The energy efficiency standards & labelling schemes of the countries located in the North-Western part of South America, which will be referred to as "Andean Region", present a heterogeneous picture. As will be shown, the national schemes of these countries are influenced by those of Mexico (i.e. indirectly by the US), of the European Union and to some extent Brazil and other Southern Cone countries. This is the case for labelling regulations and standards, and also for measurement standards, which may refer either to international, Mexican, US or Brazilian standards. With some generalisation, energy efficiency standards and labelling schemes in these countries are less characterised by alignment to international or regional references, but by some kind of eclecticism, i.e. that they draw on upon different precedents. This eclecticism reflects the geographical situation of these countries between Mexico and Central America on the one hand, and Brazil and other Southern Cone countries on the other, and in particular the economic influence of Latin America's major economies on these countries. While this situation has developed historically, since the turn of the millennium, recent standards and labelling programmes, like in Ecuador or the new programme in Colombia, confirm this heterogeneity.

3.3.1.1 Bolivia

The Bolivian Standardisation Institute IBNORCA[22] has elaborated energy labelling standards for incandescent and fluorescent lamps and for refrigerators. As mentioned in [2], the Ministry

[18] *Comité Consultivo Nacional de Normalización de Seguridad al Usuario, Información Comercial y Prácticas al Comercio* (CCNNSUICPC)
[19] *Secretaría de Medio Ambiente y Recursos Naturales* (SEMARNAT)
[20] *Fideicomiso para el Ahorro de Energía Eléctrica* (FIDE)
[21] *Ley 7447 de diciembre 1994 sobre la Regulación del Uso Racional de la Energía y Decreto reglamentario N^o 25584 de 1996.*
[22] *Instituto Boliviano de Normalización y Calidad (*IBNORCA*)*

of Hydrocarbons and Energy[23] runs an energy labelling programme, however this information could not be verified.

3.3.1.2 Colombia

In Colombia, approximately 30 energy efficiency labelling and measurement standards have been elaborated, since 2002, for a wide range of household appliances (including refrigerators and freezers, room air conditioners, gas and electric water heaters, household washing machines, various gas appliances), lighting equipment and electric motors. The "labelling standards", which were published as Colombian National Standards (NTC)[24], define the design, content and underlying algorithms of the label for a certain product, referring to the respective measurement standard (test procedure). The Colombian energy label is of the categorical type, following so far basically the original EU label. The existing standards were elaborated in the framework of the government's CONOCE[25] programme, in cooperation between the government agency *Unidad de Planificación Minero Energética* (UPME) and the Colombian national standardisation institute ICONTEC[26], including stakeholder consultations. The CONOCE Programme was launched in 2001 and most standards were elaborated in the period 2002 – 2004. Several labelling standards were subsequently reviewed and updated. So far, the labelling standards have been voluntary.

In October 2013, the Ministry of Mines and Energy (MME) published a Draft Technical Regulation for Labelling (RETIQ)[27], which includes new labelling requirements for room and central air conditioners, household and commercial refrigerators and freezers, electromagnetic and electronic ballasts, single-phase and three-phase electric induction motors, household washing machines, electric storage water heaters, gas instantaneous and storage water heaters, gas cooking ranges and ovens. The new labelling requirements are supposed to replace the existing "labelling standards", redefining labelling classes, in some cases the underlying algorithms, and the label design. The proposed generic label design combines elements from the former categorical label with elements similar to the Mexican and US labels. Energy efficiency classes and underlying algorithms are defined analogously to the classes of former and current EU regulations, although for various products algorithms from other national regulations, like e.g. Mexico and the US, are used. The first version of RETIQ also included an annex with measurement standards for the products concerned, which are based on various national and international standards. Last, but not least, the proposed regulation includes stipulations with regard to procedures for conformity evaluation (certification) and market surveillance. A revised draft of RETIQ, dated June 2014, was published by MME, inviting comments by July 3, 2014. Taking into consideration the comments received, the final draft of RETIQ was published in November 2014 and sent to the World Trade Organisation (WTO) for international consultation. It was expected that RETIQ will be published around May 2015. The final draft does not any more include the annex with measurement standards; these are now referenced separately for each product covered by RETIQ.[28]

3.3.1.3 Ecuador

In Ecuador, Technical Regulations for Energy Labelling of household appliances and other energy-using products have been developed and implemented since 2009. Until 2013, labelling regulations were implemented for household refrigerating appliances, CFLs, room air conditioners and household washing machines. Since 2013, "emergency" regulations were adopted for the following products: storage and instantaneous gas water heaters, electric storage water heaters, electric appliances for induction cooking, clothes driers, ventilators with integrated electric motors, televisions, electric ovens, microwave ovens, clothes washer-

[23] *Ministerio de Hidrocarburos y Energía (*MHE*)*
[24] *Normas Técnicas Colombianas* (NTC)
[25] *Programa de Normalización, Acreditación, Certificación y Etiquetado de Equipos de Uso Final de Energía (*CONOCE*)*
[26] *Instituto Colombiano de Normas Técnicas y Certificación* (ICONTEC)
[27] *Reglamento Técnico de Etiquetado* (RETIQ)
[28] Personal communication Luis Fernando Lopez Pineda (MME) and Omar Alfredo Baez Daza (UPME), February 2015.

driers and dishwashers. Regulations for further products and revised regulations for gas water heaters and electric storage heaters are in the process of adoption. The labelling regulations are mainly aligned with the corresponding (previous) Colombian regulations; yet also some alignment with former EU labelling regulations and Mexican NOMs can be observed. Test procedures referred to include Ecuadorian national standards, international and US standards. Minimum energy efficiency requirements apply for household refrigerating appliances, room air conditioners, household washing machines, CFLs, standby power for televisions, storage and instantaneous gas water heaters and for ventilators with integrated electric motors. All standards and regulations are issued by the Ecuadoran standardisation institute INEN[29].

3.3.1.4 Peru

In Peru, the elaboration of test procedures was initiated in 1996. In the following years, energy efficiency test procedures were developed for refrigerators and freezers, lighting equipment (lamps and ballasts), electric motors, electric water heaters, industrial boilers and solar thermal and photovoltaic systems, followed by voluntary EE labelling standards for refrigerators and freezers, household lamps and electric motors. Since 2007, minimum efficiency performance standards for CFLs are in force. According to Government Decree of 23 October 2007[30] regulating the Law for the Promotion of Efficient Use of Energy of 2000 (Law N° 27345 of 2000)[31] the Ministry of Energy and Mines (MEM) has been required to develop and implement mandatory energy efficiency labelling of energy consuming equipment and appliances.

In 2009, MEM published two documents: (i) the Guide on the Energy Efficiency Label[32] and (ii) the Guide on Minimum Energy Efficiency Standards[33]. The Guide on the Energy Label proposes the label design and the contents of the labels for industrial boilers, electric three-phase induction motors, household refrigerating appliances, electric storage water heaters, gas instantaneous water heaters, and household lamps. They are of the categorical type, similar to the EU label, and include seven energy efficiency classes A–G, with the exception of the labels of industrial boilers and electric motors, which include three energy efficiency classes A–C. The Guide on Minimum Energy Efficiency Standards proposes thresholds for the same products.

In accordance with the original mandate of 2007, MEM elaborated in 2011 Technical Regulations for Labelling for the following products: fluorescent lamps, three-phase electric motors, gas and electric instantaneous and storage water heaters, industrial package boilers and solar water heaters. Currently, guidelines and preliminary drafts for labelling and MEPS regulations for a whole range of additional products are under elaboration.[34] While some labelling regulations and test procedures published so far are aligned with international or national standards of other countries, others are genuine documents combining elements from different sources.

3.3.1.5 Venezuela

In Venezuela, labelling of refrigerators/freezers is mandatory since 1998, in addition to a voluntary labelling scheme for room air conditioners. So far, labels have been equivalent to the US Energy Guide. The labelling standards were issued by the Venezuelan Institute for Industrial Standards COVENIN[35]. In 2012, the Ministries of Electric Energy and of Commerce

[29] *Instituto Ecuatoriano de Normalización (*INEN*).*

[30] *Decreto Supremo N° 053-2007-EM del 23 de octubre de 2007: Reglamento de la Ley de Promoción del Uso Eficiente de la Energía*

[31] *Ley N° 27345 del 1 de septiembre de 2000: Ley de Promoción del Uso Eficiente de la Energía*

[32] *Ministerio de Energía y Minas – Dirección General de Electricidad: Guía de la Etiqueta de Eficiencia Energética, Enero de 2009.*

[33] *Ministerio de Energía y Minas – Dirección General de Electricidad: Guía de Estándares Mínimos de Eficiencia Energética, Enero de 2009.*

[34] In 2012, the Ministry of Energy and Mines commissioned the elaboration of draft technical regulations for energy labelling and MEPS for a wide range of products, including: electronic and electromagnetic ballasts, gas cooking ranges and ovens, electric ovens, LED lamps, combined clothes washer-driers, household washing machines, refrigerators and freezers, clothes driers, air conditioners and televisions.

[35] *Comisión Venezolana de Normas Industriales (COVENIN)*

issued a joint resolution, which enacted a new Technical Regulation on the Energy Efficiency Labelling of Air Conditioners[36]. The Technical Regulations covers different types of air conditioners and introduces a new label, which is similar to the previous EU label. It also stipulates minimum energy efficiency requirements. According to [2], CONVENIN has issued more labelling standards since 2000; this information could however not be verified.

3.3.2 Southern Cone countries (except Brazil)

The energy efficiency standards & labelling schemes of the countries located in the Southern part of South America, the so-called "Southern Cone" ("*Conosur*"), show many similarities with each other and are widely aligned with previous EU labelling regulations and international test procedures. This is the case for Argentina, Chile, Paraguay and Uruguay, while Brazil has developed its own scheme, which also has a much longer history than the programmes presented in this section.

3.3.2.1 Argentina

The Argentinean standards and labelling programme was initiated in 1996, as PROCAEH[37]. During its three years of operation (1996 – 1999), PROCAEH achieved a consensus with market actors, resulting in the publication of test procedures and labelling standards for refrigerators and freezers, as well as of a government resolution defining the responsibility of the government to introduce mandatory energy efficiency labelling for a wide range of products.[38] Due to changes in the public administration and the economic crisis at the beginning of the past decade, the programme remained inactive from 2000 to 2003. In 2003, the Argentinean National Energy Secretariat reinstated the programme as PROCAE[39].

At present, energy labelling is mandatory for refrigerators/freezers, household washing machines, air conditioners and fluorescent lamps. The labelling requirements are introduced by Administrative Order (*Disposición*) of the National Directorate of Internal Commerce[40] and refer to underlying "Technical Energy Efficiency Labelling Standards"[41]. Labelling standards have also been published for three-phase electrical motors, ballasts for fluorescent lamps, standby power/consumption, centrifugal pumps, electric storage water heaters and television receivers, as well as thermal characteristics of buildings. Labelling standards for electricity consuming products are developed and issued by the National Standardisation Institute IRAM, under the auspices of the National Energy Secretariat (SE)[42]. The Argentinean energy label is widely aligned to the design and the energy efficiency classes of former EU label, including the energy efficiency classes A–G.

Argentina has also established MEPS for refrigerators/freezers, room air conditioners and household washing machines. MEPS are implemented by Resolution of the National Energy Secretariat and establish energy efficiency thresholds in accordance to energy efficiency classes defined by the labelling standards. Although the thresholds have been gradually tightened, they are still rather weak, as they correspond to the previous EU energy efficiency classes A–C[43]. Incandescent lamps were banned from the Argentinian market by Law 26.473[44], which prohibits their import and the commercialisation since end of 2010.

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[36] *Reglamento Técnico para el Etiquetado de Eficiencia Energética en Acondicionadores de Aire (Resolución conjunta de los Ministerios del Poder Popular de Energía Eléctrica No 054 y de Comercio No 071 de fecha 16/11/2012).*

[37] *Programa de Calidad de Artefactos Energéticos para el Hogar (PROCAEH).*

[38] *Resolución No 319/99 ex-SICyM del 14 de mayo de 1999: "Adoptándose medidas en relación a la comercialización de aparatos eléctricos de uso doméstico que cumplan determinadas funciones".*

[39] *Programa de Calidad de Artefactos Energéticos (*PROCAE*).*

[40] *Dirección Nacional de Comercio Interior* of the Ministry of Economy and Public Finance.

[41] *Normas Técnicas de Etiquetado de Eficiencia Energética.*

[42] *Secretaría de Energía* of the Ministry of Federal Planification, Public Investment and Services.

[43] Refrigerators, refrigerator-freezers and freezers: Resolutions 396:2009, 198:2011 and 682:2013, which subsequently define minimum energy efficiency requirements equivalent to label classes C (since 2009 for refrigerators and refrigerator-freezers and since 2011 for freezers) and B (since 2013 for all appliances); Split and compact room air conditioners: Resolutions 1542:2010, 1407:2011, 814:2013 and 228:2014, which define gradually the minimum energy efficiency requirements in cooling and heating mode – currently equivalent to label class A for cooling mode and equivalent to class C for heating mode for air conditioners with a cooling capacity of ≤ 7 kW;

In the case of gas appliances, the National Regulatory Agency for Gas (ENERGAS)[45] has the legal authority to develop and to implement labelling standards and MEPS. So far, mandatory labelling standards for domestic cooking appliances (NAG-312/2010) and for instantaneous gas water heaters (NAG-313/2009, Addendum N° 1/2012) were published. Labelling standards for room heaters and for storage gas water heaters were still under public discussion and were expected to be published in the second half-year of 2014.[46] For all gas appliances which are regulated by ENARGAS, minimum energy performances requirements apply.

3.3.2.2 Chile

The Energy Efficiency Standards and Labelling Programme of Chile was initiated as part of the National Energy Efficiency Program (PPEE)[47], which was created in 2005. With an annual budget of almost 30 Mio. US$ in 2009, PPEE was one of the most visible and comprehensive energy efficiency programmes of the Region. Since 2010, the Chilean Energy Efficiency Agency AChEE[48] continues the previous work of PPEE.

So far, mandatory labelling has been introduced for refrigerators/freezers, incandescent and fluorescent lamps, ballasts for fluorescent lamps, household washing machines, room air conditioners, three-phase electric induction motors and standby power for various electric and electronic devices, including microwave ovens, TV decoders, audio and video equipment, and printers. The labelling requirements are based on energy labelling standards ("*normas de eficiencia energética*") published as Official Chilean Standards[49], and are introduced on a mandatory basis by so-called "Protocols" (*Protocolos*)[50] and Resolutions issued by of the Superintendency for Electricity and Fuels (SEC)[51]. Energy labelling standards for additional products are under elaboration.

The Chilean Ministry of Energy (MoE) has worked since 2009 on the elaboration of MEPS for lamps, which became mandatory in December 2013, and which effectively phases out incandescent lamps[52]; followed by a MEPS for refrigerators, which was submitted to public consultation in August 2014. A MEPS for electric motors is currently under elaboration. MoE has received technical assistance from the Environmental Energy Technologies Division of the Lawrence Berkeley National Laboratory (LBNL) [4] and issued, in 2012, a regulation which defines the criteria and procedure to be applied in establishing MEPS.[53] The regulation requires, i.a., the elaboration of a regulatory impact assessment and consultation and coordination procedures among government entities and the public.

3.3.2.3 Paraguay

The National Standardisation Institute INTN has only recently issued standards with regard to energy labelling. In July 2013, a standard defining the general labelling design was issued, following by a labelling standard for air conditioners in March 2014. In April 2014, a draft labelling standard for refrigerators/freezers was issued. These standards, which are still voluntary, are influenced by the respective previous EU, Colombian, Argentinian and Chilean

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Household washing machines: Resolution 684:2013, defining a minimum energy efficiency requirement equivalent to label class B.

[44] *Ley 26.473. Prohíbese a partir del 31 de diciembre de 2010, la importación y comercialización de lámparas incandescentes de uso residencial general en todo el territorio de la Républica Argentina. Sancionado: Diciembre 17 de 2008. Promulgado de hecho: Enero 12 de 2009.*

[45] *Ente Nacional Regulador de Gas* (ENARGAS).

[46] Personal communication Salvador Gil (ENARGAS / *Universidad Nacional de San Martín*), August 2014.

[47] *Programa País de Eficiencia Energética* (PPEE).

[48] *Agencia Chilena de Eficiencia Energética* (AChEE).

[49] *Normas Chileans Oficiales* (NCh).

[50] The Protocols issued by SEC mainly refer to certification procedures, measurement standards and energy labelling standards (as far as they are published as Official Chilean Standards) to be observed on a mandatory basis.

[51] *Superintendencia de Electricidad y Combustibles* (SEC).

[52] *Resolución 60 extenta (2013): Fija estándar mínimo de eficiencia energética para lámparas no direccionales para iluminación general y su programa de implementación.* The Resolution defines a minimum efficiency equivalent to label class C and a timetable for phasing out incandescent lamps of different capacities.

[53] *Reglamento N° 97 del 15/11/2011 que establece el procedimiento para la fijación de estándares mínimos de eficiencia energética y normas para su aplicación (Diario Oficial de la República de Chile del 14/05/2012).*

labelling standards and regulations. Draft labelling standards for incandescent and fluorescent lamps are under discussion.

3.3.2.4 Uruguay

In 2005, Uruguay started its National Energy Efficiency Programme, initially with the cooperation of the Global Environment Facility (GEF) and the World Bank[54]. Part of this ongoing programme[55] are the elaboration and implementation of energy efficiency labelling for electric and gas appliances and other energy-using products. So far, energy labelling standards have been issued by the National Standardisation Institute UNIT[56] for household refrigerating appliances, household washing machines, household tumble driers, gas cooking appliances, electric and gas storage water heaters, gas wall-mounted combined water heaters, air conditioners and heat pumps, incandescent and fluorescent lamps and electric three-phase induction motors. In 2009, the Ministry of Industry, Energy and Mining issued a framework regulation for mandatory energy labelling.[57] So far, energy labelling is mandatory for compact fluorescent lamps, electric storage water heaters and household refrigerating appliances.

3.3.3 Central America

Energy efficiency standards and regulations were also implemented or are under development in various Central American countries, notably in Costa Rica and Nicaragua. The standards and labelling schemes of these countries are mainly influenced by either Mexican energy efficiency standards or the corresponding COPANT standards.[58]

3.3.3.1 Costa Rica

Costa Rica was the first country in Central America to introduced energy efficiency standards and labelling, following the Law on Regulation of the Rational Use of Energy of 1994[59]. Currently, voluntary technical standards for energy efficiency have been issued by the national standardisation institute INTECO[60] for household refrigerators and freezers, commercial refrigerators, various types of air conditioners, three-phase electric induction motors, incandescent lamps and CFLs. These cover measurement standards (test procedures), energy labelling and MEPS. The labelling standards and MEPS are either partly aligned to the corresponding Mexican Official Standards (NOM) or equivalent to the corresponding COPANT standards.

For CFLs, as well as for household refrigerators and freezers, the Government has implemented, in 2000 and 2001 respectively, corresponding decrees, rendering minimum standards and labelling mandatory. Also, the national electricity company ICE[61] and INTECO have issued an energy efficiency label (*Sello EnergICE - INTECO*) which has been applied so far for compact fluorescent lamps. ICE has also issued a guide for the interpretation of the national and foreign (US and Mexican) energy efficiency labels for refrigerators. In accordance with Law 7447/1994, products which do not comply with the MEPS defined by the Government, are subject to a surcharge of 30% with regard to the selective excise duty (*impuesto selectivo de consumo*).

3.3.3.2 Nicaragua

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[54] *Proyecto de Eficiencia Energética* (http://www.gefonline.org/projectListSQL.cfm)
[55] See http://www.eficienciaenergetica.gub.uy/
[56] *Instituto Uruguayo de Normas Técnicas* (UNIT).
[57] *Decreto No 429/009 – Equipos y artefactos que consumen energía. Comercialización. Cumplimiento de Normas Unit.*
[58] Work on energy efficiency standards is also ongoing in Honduras. So far, no information of such programmes in other Central American countries could be verified.
[59] See footnote 21.
[60] *Instituto de Normas Técnicas de Costa Rica (*INTECO*).*
[61] *Instituto Costarricense de Electricidad* (ICE).

The National Assembly of Nicaragua has issued mandatory technical standards (NTON[62]) for energy efficiency of various energy-consuming products: household refrigerators and freezers, commercial refrigerators, various types of air conditioners, three-phase electric induction motors, incandescent lamps and CFLs, covering measurement standards (test procedures), mandatory energy labelling and MEPS. The labelling standards and MEPS are either partly aligned to the corresponding Mexican Official Standards (NOM) or equivalent to the corresponding COPANT standards. Measurement standards refer to those defined in the corresponding NOM, with some additional references to international and US measurement standards. Labels are equivalent to the corresponding Mexican energy label, with the exception of the label for lamps, which is equivalent to the label proposed by COPANT, in accordance with the former EU label.

3.3.4 COPANT

In an effort to provide harmonised energy labelling standards, the Technical Committee Energy Efficiency and Renewable Energies (CT 152) of the Pan American Standards Commission (COPANT)[63] is working since more than ten years on Pan American energy efficiency standards, which are of voluntary application.

So far, two COPANT standards have been issued:

- COPANT 1707:2006 - Energy efficiency. Domestic refrigerators, freezers and combinations. Specifications and labelling.[64]
- COPANT 1708:2006 - Energy efficiency. Household incandescent and similar lamps. Specifications and labelling.[65]

COPANT 1707:2006 defines a categorical energy label with seven energy efficiency classes A–G, which is similar to the previous EU label, and includes two alternative methods for defining the energy efficiency classes, The first method is identical to Directive 94/2/CE[66], including the same categories of products and based on an ambient test temperature of 25^{o}C, while the alternative method is based on the Brazilian categorisation of products and an ambient test temperature of 32^{o}C. The standard refers to international ISO measurement standards, including some clarifications. Household refrigerating appliances commercialised in Mexico have to comply with the requirements of NOM-015-ENER-2002. COPANT 1708:2006 is equivalent to the EU Directive 98/11/EC[67].

Draft COPANT energy efficiency standards have so far been elaborated for: Window-type air conditioners (*Proyecto* COPANT 152-002); Compact, circular and tubular fluorescent lamps (*Proyecto* COPANT 152-004); Three-phase electric induction motors (*Proyecto* COPANT 152-005); Household washing machines (*Proyecto* COPANT 152-007); Instantaneous electric water heaters (*Proyecto* COPANT 152-008) and Storage type electric water heaters for household use (*Proyecto* COPANT 152-009). In addition, COPANT has issues a pre-draft standard for split air conditioners.

4 Alignment and harmonisation

4.1 Alignment with EU and US standards and labelling schemes

Basically, two types of standards and labelling programmes exist in Latin America:

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[62] *Normas Técnicas Obligatorias Nicaraguënses* (NTON).

[63] The following national standardisation institutes are members of CT 152 of COPANT: IRAM, IBNORCA, ABNT, INN, ICONTEC, INTECO, NC, COGUANOR, JBS, DGN, INDECOPI, DIGENOR, SCC and ANSI. Observers are: BNSI, AENOR, UNIT and FONDONORMA.

[64] *Norma COPANT 1707:2006 - Eficiencia energética. Refrigeradores, congeladores u combinados de uso doméstico. Especificaciones y etiquetado.*

[65] *Norma COPANT 1708:2006 - Eficiencia energética. Lámparas incandescentes de uso doméstico y similares. Especificaciones y etiquetado.*

[66] Commission Directive 94/2/EC of 21 January 1994 implementing Council Directive 92/75/EEC with regard to energy labelling of household electric refrigerators, freezers and their combinations.

[67] Commission Directive 98/11/EC of 27 January 1998 implementing Council Directive 92/75/EEC with regard to energy labelling of household lamps.

First, the Mexican standards and labelling programme, whose main focus is on minimum energy performance standards. From its very beginning in 1992, the Mexican programme was designed in a similar way as the US energy efficiency standards programme. The main focus of these programmes is on MEPS, while labels are considered as a secondary instrument of consumer information. The Mexican model is also the basis for the standards and labelling programmes in Central America.

Second, the standards and labelling programmes of most South American countries, that started with the development of test procedures and labelling standards, and have moved (or are still moving) from voluntary to mandatory schemes. While some countries have moved rather quickly from voluntary to mandatory labelling, it has taken other countries longer periods (from several years to a decade) to enact the first mandatory labels. A particular striking example is Colombia, where a very complete set of testing procedures and energy efficiency labels has been developed since 2001 by the government agency UPME[68], in cooperation with the national standardisation institute ICONTEC, but labelling will only become mandatory in 2015.

Another distinctive element among Latin American standards and labelling programmes is the label design. While Mexico and Central America follow in principle the US and Canadian label designs, most South American countries have adopted category labels similar to the EU label, although with some exceptions: while Colombia and Ecuador have incorporated some elements of the North American label designs, the label design in Venezuela has been, until recently, fully aligned with the North American models. Notably, some Central American countries and Venezuela have recently introduced labels for certain products which follow the EU design. Figures 1 and 2 include examples of energy labels discussed in this paper.

Regarding measurement standards (test procedures), the picture is even more heterogeneous. Brazil and Mexico have developed own national measurement standards (NBR[69] and NOM respectively), which are based on ISO-IEC standards and US test procedures respectively, with some modifications. Also other countries of the Region have adopted national standards for the measurement of the energy performance of energy-using products, which are – to varying degrees – aligned with ISO-IEC, NBR, US, NOM or other international, regional or national standards, including some regional standards elaborated by the Pan American Standards Commission (COPANT). In the case of alignment of national measurement standards with international standards, some national standards are fully homologated with the corresponding ISO-IEC standard, while in other cases, minor or major modifications were made.

Regarding Minimum Energy Performance Standards, a distinction can be made between Mexico, where the focus was on MEPS – following US rulemaking – right from the beginning of the programme in 1995, and Brazil, who started to implement MEPS since 2001. Argentina and Chile have developed MEPS for a limited number of products (refrigerators-freezers and lamps, in the case of Argentina also air conditioners and household washing machines) since 2009. Since 2013, Ecuador and Nicaragua have promulgated technical regulations which define MEPS for a rather wide range of products. Venezuela has recently introduced a MEPS for air conditioners. It should be mentioned that the methodology to define thresholds of MEPS differs among countries. While Chile, for instances, applies a cost-benefit analysis in accordance to *Reglamento 97/2011*, the thresholds defined in Argentina appear to be fixed in negotiation with stakeholders.

4.2 Intra-regional alignment

In addition to the alignment with the EU and US standards and labelling schemes, also some tendencies to intra-regional alignment can be observed, both in the Andean and the Southern Cone sub-regions.[70]

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[68] *Unidad de Planeación Minero-Energética (*UPME*).*
[69] *Normas Brasileiras (NBR),* published by *Associação Brasileira de Normas Técnicas (ABNT).*
[70] A detailed analysis of labelling regulations and standards in each country, and of intra-regional alignment is part of a forthcoming report by the author [5].

4.2.1 Colombia, Ecuador, Peru and Venezuela

4.2.1.1 Colombia

The new Technical Regulation for Labelling (RETIQ) includes in one single document ("*Anexo General*") a chapter on general requirements for labelling[71], which defines i.a. the generic label design and the contents of the label, the requirements for exhibiting the label, and the promotion of efficient products by the Government, and the specific labelling requirements for each of the products previously mentioned in Section 3.3.1[72]. The new Colombian label is a "categorical" label, which includes various energy efficiency classes (typically A–G or A–E) and is embedded into a yellow label, which resembles the Mexican and US labels. For several products (commercial refrigerators and freezers, electromagnetic and electronic ballasts, gas instantaneous and storage water heaters), the label only includes a numerical indication of product characteristics, instead of a graphical representation of energy efficiency classes.

In general, RETIQ presents a heterogeneous approach, merging elements from the previous Colombian (EU like) and Mexican label designs, and referring to different measurement standards and labelling regulations, including ISO/IEC, ANSI/ASHRAE, Mexican and national measurement standards; EU Commission Delegated Regulations, previous EU labelling directives and Mexican Official Standards (NOM). Except numerous references to Mexican NOM standards, there is no evidence of alignment with other standards or regulations in the Region.[73]

4.2.1.2 Ecuador

The Ecuadorian labelling regulations are mainly aligned with the corresponding Colombian (voluntary) labelling standards; yet also some alignment with former EU labelling regulations, Mexican NOMs and Brazilian regulations[74] can be observed. Test procedures referred to include Ecuadorian national standards, international and US standards. The general tendency to align with (previous) Colombian labelling standards, despite the fact that these are being revised, means that the current, rather new, Ecuadorian regulations and standards may have to be revised also. Minimum energy performance requirements usually refer to energy efficiency classes A or B (in the case of categorical labels) or are equivalent to the MEPS defined by the corresponding NOM standards.

4.2.1.3 Peru

Like other Latin American countries, Peru knows various "layers" of documents which define the energy labelling requirements and – in some cases – also minimum energy efficiency requirements: (i) Energy efficiency labelling "standards", which are issued by the Peruvian Standardisation Institute INDECOPI[75] as Peruvian Technical Standards (*Norma Técnica Peruana* – NTP), and (ii) technical regulations, which render the "labelling standards" mandatory. The "labelling standards" usually refer to other NTPs, which define the methods of measurement (test procedures) for the corresponding product.

While Peruvian labelling standards follow in principle the design of the previous EU label, there are some differences, e.g. different colour codes, which stem from the label design according to the previous Colombian standard NTC 5100:2002[76]. The labels for gas and electric instantaneous and storage water heaters also include safety information. Most NTPs

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[71] *Ministerio de Minas y Energía: Anexo General Reglamento Técnico de Etiquetado, Octubre de 2013. Capítulo 2: Requisitos Generales del Etiquetado.*
[72] *Ibid. Capítulo 3: Requisitos Específicos de Etiquetado de Equipos.*
[73] In the final draft of RETIQ of November 2014, the Technical Regulation does not include anymore the "Annex of Measurement Standards" ("*Anexo de Ensayo del Reglamento Técnico de Etiquetado – RETIQ*"), but establishes for each product the test method and the equivalent test standard(s) to be applied. These are in general in line with the reference standards mentioned in this paragraph.
[74] For domestic ventilators and microwave ovens.
[75] *Instituto Nacional de Defensa de la Competencia y de la Protección de la Propiedad Intelectual* (INDECOPI)
[76] Norma Técnica Colombiana NTC 5100:2002 Etiqueta Genérica Informativa de Desempeño Energético.

and technical regulations refer to previous Colombian labelling standards, which results in a similar problem like in Ecuador. While the labelling standards for incandescent and fluorescent lamps are aligned to the previous Directive 98/11/EC[77], others – like the standards for refrigerators, refrigerator-freezers and freezers – are influenced by Mexican NOM standards, and the standards for water heaters and industrial boilers appear to be own elaborations with reference to various national and international labelling regulations and measurement standards.

4.2.1.4 Venezuela

The history of energy efficiency standards and labelling in Venezuela is characterised by early adoption of labelling standards – at the end of the 1990ties, more than a decade of non-activity and taking up the programme again since 2012. So far, energy labelling standards were issued for refrigerators, refrigerator-freezers and freezers and for window-type air conditioners in 1999 and 2000 respectively. Both labelling standards define labels equivalent to the US Energy Guide, featuring a reference range of annual energy consumption (kWh/year) and Energy Efficiency Ratios (EER) respectively, and refer to Venezuelan measurement standards, which appear to be equivalent to the respective US test procedures (at the time of issuing the standards).

In 2012, the Ministries of Popular Power of Electric Energy and of Commerce issued a joint resolution, which enacted a new Technical Regulation on the Energy Efficiency Labelling of Air Conditioners, which includes a minimum energy efficiency requirement[78]. The Technical Regulation includes window-type, package terminal air conditioners, split air conditioners and central ducted air conditioners. For each type of air conditioners, energy efficiency classes are defined based on the energy efficiency ratio (EER) of the product. The energy efficiency classes are given for cooling mode only and are different from those defined in Directive 2002/31/CE[79] and Commission Delegated Regulation (EU) No 626/2011[80]. The Technical Regulation defines energy labels with six energy efficiency classes A–F, refers to various ISO and IEC measurement standards and stipulates as minimum energy efficiency requirement class C.[81]

4.2.2 Southern Cone countries (except Brazil)

4.2.2.1 Argentina

Argentinean test procedures for energy performance are equivalent to the respective ISO/IEC standards, in some cases also with European EN standards.

Also, most of the energy labelling standards issued by the national standardisation institute IRAM[82] follow the previous EU labelling directive and, in the case of televisions, even the respective Commission Delegated Regulation[83]. The energy labels defined by these standards are similar to the previous EU labels, with some notable differences, e.g. in the case of household washing machines. The labelling standard for electric storage water heaters is equivalent to the draft standard COPANT 152-009[84]. Like EU labelling directives and regulations, the Argentinean labelling standards require a product fiche to be provided with the product. While Argentinean labelling regulations are largely aligned with the EU, they have influenced the labelling schemes of other Southern Cone countries, notably Paraguay and Uruguay, as will be shown below.

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[77] See footnote 67.
[78] See footnote 36.
[79] Commission Directive 2002/31/EC of 22 March 2002 implementing Council Directive 92/75/EEC with regard to energy labelling of household air-conditioners.
[80] Commission Delegated Regulation (EU) No 626/2011 of 4 May 2011 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of air conditioners.
[81] According to CEPAL (2013), CONVENIN has issued more labelling standards since 2000. This information could however not be verified.
[82] *Instituto Argentino de Normalización y Certificación (*IRAM*).*
[83] Commission Delegated Regulation (EU) No 1062/2010 of 28 September 2010 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of televisions.
[84] See Section 3.3.4.

Minimum energy performance standards have been implemented in Argentina since 2009 by Resolutions of the Energy Secretariat of the Ministry of Federal Planning, Public Investments and Services[85]. Currently minimum energy efficiency requirements correspond to energy class B (refrigerators, refrigerator-freezers and freezers; household washing machines) and class A (split and compact air conditioners in cooling mode; class C for heating mode). While there is no MEPS defined for lamps, the commercialisation of incandescent lamps is forbidden since end of 2010, by Law 26.473:2009.

4.2.2.2 Chile

Chilean test procedures for energy performance are generally aligned with the respective ISO/IEC standards.

The Chilean energy label generally follows the design and the contents of the previous EU energy label, including identical energy efficiency classes. Some minor differences refer to additional information provided and different dimensions of some labels. Like the Argentinean scheme, also Chilean regulations have influenced the elaboration of labelling standards and regulations in Paraguay and Uruguay. Chile appears the only country in the sub-region, which applies a rigorous cost-benefit analysis to establish MEPS (see Section 3.3.2).

4.2.2.3 Paraguay

The labelling standards issued so far in Paraguay are also similar to the previous EU labelling directives, yet there are apparently in the first place influenced by national regulations of Argentina (NP 51 002 14 for air conditioners), Chile (Draft standard NP 51 003 14 for refrigerators/freezers) and Colombia (NP 51 001 13, defining the generic label design). This heterogeneity leads to inconsistencies, like contradicting label dimensions and colour codes for the arrows representing the energy efficiency classes. While the energy efficiency classes for air conditioners and refrigerators/freezers are identical to those defined in the European Directive 2002/31/EC[86], the Paraguayan labels also include efficiency classes A+, A++ and A+++, which correspond to energy efficiency indices (EEI), energy efficiency ratios (EER) and coefficients of performance (COP), which are not directly comparable with those of the current Commission Delegated Regulations No 1060/2010[87] and No 626/2011[88], because of different metrics and indicators. NP 51 002 14 and draft standard NP 51 003 14 refer to the respective ISO measurement standards.

4.2.2.4 Uruguay

Also in the case of Uruguay, most labelling regulations are at least similar to the previous EU labelling directives, although they are in the first place equivalent with "labelling regulations" from Argentina (refrigerators/freezers, washing machines, air conditioners, lamps), Chile (refrigerators/freezers, air conditioners, lamps) or COPANT (draft) labelling standards (refrigerators/freezers, air conditioners, lamps, three-phase electric motors). Some labelling standards include two alternative or complementary labelling scales, like the standard for washing machines, which defines labelling scales for two temperatures (15 ^{o}C and 60 ^{o}C), the standard for air conditioners, with two label scales for cooling and heating, and the standard for gas ranges and ovens, with two scales, one for the range and another for the oven burners. The dimensions of the Uruguayan labels are not always the same like those of the EU labels, and the Uruguayan labelling standards and regulations do not require a fiche.

Test procedures referenced in the "labelling regulations" are generally recent UNIT-IEC, IEC or ISO standards, with some references to Brazilian NBR standards, e.g. for gas cooking ranges and ovens.

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[85] *Secretaría de Energía del Ministerio de Planificación Federal, Inversión Pública y Servicios.*
[86] See footnote 79.
[87] Commission Delegated Regulation (EU) No 1060/2010 of 28 September 2010 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of household refrigerating appliances.
[88] See footnote 80.

4.2.3 Central America

As an example for the energy efficiency standards and labelling programmes in Central America, reference is made to the labelling and minimum energy performance standards issued in *Nicaragua* as mandatory national standards (Normas Técnicas Obligatorias Nicaraguënses – NTON). These standards are mainly aligned with the corresponding Mexican Official Standards (NOM), although some minimum performance requirements appear to be less stringent in the corresponding NTON or refer to previous editions of the NOM standard. In the case of incandescent lamps, CFLs and window-type air conditioners, the Nicaraguan standards refer to the respective COPANT standards and define categorical labels. In all other cases labels with continuous scales, according to NOM, are applied.

5 Discussion

Brazil was the first country in Latin America – and one of first countries in the world – that developed and implemented an energy efficiency standards and labelling programme. Starting from voluntary labelling, the programme evolved into a full-scale programme including mandatory labelling and – more recently – minimum energy efficiency standards for a wide range of products. Although influenced to some extent by the then incipient EU labelling scheme (in particular with regard to the label design), Brazil developed from the very beginning its own scheme, which responds to characteristic parameters like the climatic conditions of the country and specific consumer habits.[89]

While the Brazilian programme has recently shown a strong dynamic, its influences on other countries has been limited, even within the MERCOSUR sub-regional customs union and trading bloc. The main reasons may be the orientation of Argentina towards the EU labelling scheme [6], which was subsequently also adopted by the other Southern Cone countries Chile, Uruguay and – most recently – Paraguay. I.e. that Brazil, who was the pioneer of energy efficiency standards and labelling in South America, did not succeed to induce the other countries of the Region, or even of the Southern Cone sub-region, to align with its programme.

In contrast to the originality of the Brazilian energy efficiency standards and labelling programme, the Mexican scheme – from its very beginning – has been clearly aligned to another national scheme, viz. that of its northern neighbour, the United States of America. Considering that Canadian energy efficiency standards and labels are almost identical to the US system, this means that there is a high degree of alignment in the North American sub-region. The alignment of the Mexican programme with those of the US and Canada concerns the MEPS, the label design and the measurement standards with are included in the Official Mexican Energy Efficiency Standards (NOM-ENER), although in some cases the alignment is only partial and some NOM-ENER lack behind the ambition and the scope of their US references [7]. There are no indications that Mexico could change this approach in favour of other energy labelling schemes, international measurements standards or a different model to establish MEPS. The Mexican EE S&L scheme has considerable influence on other countries of the Region, in particular Central American and also some Andean countries.

The energy efficiency standards and labelling schemes of Colombia, Ecuador, Peru and Venezuela do not show a clear alignment to any single national or regional scheme. As has been shown, labelling standards and regulations for individual products may be aligned – or at least be influenced – by EU regulations, Mexican standards, standards and regulations from other South American countries and – to a lesser extent – directly by US rulemaking. Analogously, the measurement standards applied in these countries can vary from international ISO-IEC standards to Mexican, US (ANSI-AHAM, NEMA, etc.) to genuine own national standards, which combine elements from various reference standards. A major shortcoming of the labelling regulations recently published in Ecuador and in Peru is their

[89] E.g., Brazilian test procedures for refrigerators are adapted to the relevant climate class, and the label for household washing machines primarily refers to the energy efficiency of washing cycles using water at ambient temperature (20 ^{o}C).

reference to outdated Colombian labelling standards (which are being replaced by the new Technical Regulation for Labelling (RETIQ). Also, the "home made" character of several Peruvian measurement standards and labelling regulation isolates these standards and regulations from major international schemes and trends. MEPS have been developed and implemented in Ecuador and to some extent in Venezuela.

As has been shown, the energy labelling standards of Argentina, Chile, Uruguay and Paraguay are generally aligned with the previous EU labelling directives, i.e. EU Directive 92/75/EEC[90] and the "implementing" directives for different energy-consuming products. This means, that energy efficiency classes and their underlying metrics correspond to the level of ambition in the EU of the period 1992 to 2003, before the new EU Labelling Directive 2010/30/EU[91] was enacted in 2010. While some labelling standards in Chile, Uruguay and Paraguay have taken into consideration amendments of various EU implementing directives (adding additional energy efficiency classes A+ and A++), only the Argentinean labelling standard for televisions is equivalent to the respective Commission Delegated Regulation under Directive 2010/30/EU. Argentina, Chile and Uruguay also developed labelling standards which do not exist in the EU, like for electric motors, ballasts and standby power, or which did previously not exist in the EU, like water heaters.

Alignment with EU labelling directives is strongest in Chile and also predominant in Argentina. While there is also strong alignment in Uruguay and Paraguay, labelling standards in these countries refer in the first place to Argentinean and Chilean labelling standards, i.e. that the alignment with the EU is mainly indirect. The influence from other national standards of the Latin American Region are rather limited. While Chilean labelling standards include only one reference to a Mexican standard, Uruguayan labelling standards tend to incorporate references to Brazilian standards. In the case of Paraguay, a previous Colombian standard defining the generic label design, served as example. While several MEPS have been implemented in Argentina, Chile has recently started the development and implementation of MEPS, based on a regulatory impact assessment based on cost-benefit analysis.

The labelling standards and regulations of Costa Rican and Nicaraguan, finally, show a major alignment with Mexican energy efficiency standards (NOM-ENER), although some Costa Rican and Nicaraguan labelling standards are aligned with the respective COPANT (draft) standards.

6 Conclusions

In contrast to the European Union, energy efficiency standards and labelling schemes in Latin America have been developed by national programmes, with no, or very little, supranational coordination. While this situation has grown historically, reflecting factors like the predominant economic and trade relations of individual countries with e.g. the United States and Europe and the related technological influences, it is also an indication of the lack of economic integration of Latin America, i.e. of the failure of cooperation schemes like the Mercosur, the Andean Community of Nations (CAN), the Union of South American Nations (UNASUR) or the Central American Integration System (SICA) to create common rules and standards with regard to energy using equipment. Mexico, on the other hand, is member of the North American Free Trade Agreement (NAFTA) and of the North American Energy Cooperation, which facilitates the alignment of the Mexican energy efficiency standards with those of the United States and Canada.

As a result of this lack of supranational coordination, Latin American shows the heterogeneous picture presented in this paper, with varying degrees of alignment and harmonisation among national schemes, and a notable lagging behind recent international developments, which involve more stringent energy efficiency requirements both with regard to MEPS and energy labelling.

[90] Council Directive 92/75/EEC of 22 September 1992 on the indication by labelling and standard product information of the consumption of energy and other resources by household appliances.
[91] Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products.

The elaboration of Pan-American voluntary standards by COPANT is probably the only lasting effort towards harmonisation of energy efficiency standards in the Region, which however – due to its voluntary character and lengthy procedures – has so far only very limited impact. While several initiatives by international organisations to foster intra-regional cooperation on standards and labelling programmes in the past decade, did not result in any practical results[92], more recent initiatives, like the REGATTA Programme[93], appear to be more focused on the implementation of minimum energy performance standards than on the harmonisation of energy efficiency standards and labelling regulations in Latin America.

As has been demonstrated in this paper, convergence of the various national energy efficiency standards and labelling regulations is not only a pending issue in Latin America, but will require a major shift in the prevailing trend to develop and implement such programmes almost exclusively at the national level. It is hoped that this paper will contribute to raise the awareness of policy makers in Latin America and of the international standards and labelling community, in order to improve national schemes and achieve higher degrees of alignment and harmonisation.

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[92] In particular, initiatives by the United Nations Development Programme (UNDP), which aimed at sub-regional harmonisation of national standards and labelling programmes in the Andean and Southern Cone (Mercosur) sub-regions.

[93] REGATTA is the "Regional Gateway for Technology Transfer and Climate Change Action in Latin America and the Caribbean" which is implemented by the United Nations Environment Programme (UNEP) – see http://www.cambioclimatico-regatta.org. Together with UNDP, the International Copper Association (ICA), CLASP and the Natural Resource Defense Council (NRDC), the Programme has recently launched the "*Alianza Global de Productos y Equipos Eficientes en América Latina y el Caribe*" (http://www.cambioclimatico-regatta.org/index.php/es/equipos-de-refrigeracion-eficientes-en-alc).

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Table 1: Regulations for energy labelling and minimum energy performance standards in Brazil (March 2014)

Products	**Energy labelling**			**MEPS**	
	Ordinance N° / year	Character	Status	Ordinance N° / year	Year of application
Household refrigerators	20/2006	Mandatory	Under revision	326/2011	2011 – 2013
Household washing machines	185/2005	Mandatory	Under revision	–	–
Tumble dryers	–	Mandatory	To be published in 2014	–	–
Gas water heaters	413/2011 182/2012	Mandatory	Monitoring implementation	324/2011	2011 – 2013
Electric water heaters (showers, taps, tankless water heaters, tank water heaters)	–	Mandatory	To be published in 2014	–	–
Systems and equipments for solar water heater	352/2012	Mandatory	Monitoring implementation	–	–
Systems and equipment for photovoltaic energy	4/2011	Mandatory	Implemented	–	–
Centrifugal pumps	455/2010	Mandatory	Monitoring implementation	–	–
Air conditioners	7/2011 410/2013	Mandatory	Implemented Monitoring implementation	323/2011	2011 – 2014
Fans and air circulators	20/2012	Mandatory	Monitoring implementation	–	–
Ceiling fans	113/2008	Mandatory	Implemented	–	–
Televisions (cathode ray tube)	267/2008	Mandatory	Under revision	–	–
Televisions (plasma, LCD and projection)	85/2009	Mandatory	Under revision	–	–
Computers and peripherics	170/2012	Voluntary	Implemented	–	–
Gas stoves and ovens	400/2012	Mandatory	Monitoring implementation	325/2011	2011 – 2013
Commercial electric ovens	446/2012	Mandatory	Monitoring	–	–

			implementation		
Microwave ovens	499/2011	Mandatory	Monitoring implementation	–	–
Water drinking fountains	191/2003	Mandatory	Under revision	–	–
Incandescent lamps for domestic use	283/2008	Mandatory	Implemented	1007/2010	2012 – 2017
Incandescent lamps for decorative use	296/2008	Voluntary	Implemented	–	–
Compact fluorescent lamps	489/2010	Mandatory	Monitoring implementation	1008/2010	2012 – 2013
Linear fluorescent lamps	–	Voluntary	To be published in 2014	–	–
LED lamps	–	Voluntary	To be published in 2014	–	–
High pressure sodium vapour lamps	483/2010	Mandatory	Implemented	–	–
Luminaires for sodium vapour and metal halide lamps	–	Mandatory	To be published in 2014	–	–
Photoelectric relays	–	Mandatory	To be published in 2014	–	–
Luminaires for LED lamps	–	Mandatory	To be published in 2014	–	–
Electromagnetic ballasts for high pressure sodium vapour and metal halide lamps	454/2010	Mandatory	Implemented	959/2010	2011 – 2012
Three-phase squirrel cage electric induction motors	488/2010	Mandatory	Implemented	553/2005	2010
Insultating liquid filled distribution transformers	378/2010	Mandatory	Implemented	–	–
Car tyres	544/2012	Mandatory	Monitoring implementation	–	–
Wind turbines	–	Voluntary	Under development for 2013	–	–

Source: Personal communication M. Borges, *Programa Brasileiro de Etiquagem* (PBE), March 2014

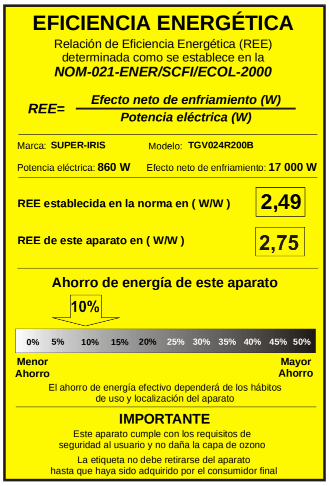
Table 2: Official Mexican Energy Efficiency Standards (March 2015)

No. of Standard (includes year of publication)	**Product / system**	**Scope**
NOM-001-ENER-2014	Vertical centrifugal pumps with external motor	Energy efficiency: limits and test procedure
NOM-002-SEDE/ENER-2014	Distribution transformers	Safety requirements and energy efficiency
NOM-003-ENER-2011	Gas water heaters for domestic and commercial use	Energy efficiency: limits, test procedure and labelling
NOM-004-ENER-2014	Clean water pumps and motor pumps	Energy efficiency: limits, test procedures and labelling
NOM-005-ENER-2012	Household washing machines	Energy efficiency: limits, test procedure and labelling
NOM-006-ENER-2014	Pumping systems for deep wells	Electromechanic energy efficiency in operation: limits and test procedures
NOM-007-ENER-2004	Lighting systems in non-residential buildings	Energy efficiency
NOM-008-ENER-2001	Buildings, building envelope of non-residential buildings	Energy efficiency
NOM-009-ENER-1995	Industrial thermal insulation	Energy efficiency
NOM-010-ENER-2004	Submersible motor pumps for deep wells	Energy efficiency: limits and test procedure
NOM-011-ENER-2006	Central air conditioners	Energy efficiency: limits, test procedures and labelling
NOM-013-ENER-2013	Street lighting systems	Energy efficiency
NOM-014-ENER-2004	Single-phase electric AC squirrel cage induction motors	Energy efficiency: limits, test procedure and marking
NOM-015-ENER-2012	Household refrigerators and freezers	Energy efficiency: limits, test procedures and labelling
NOM-016-ENER-2010	Three-phase electric AC squirrel cage induction motors	Energy efficiency: limits, test procedure and marking
NOM-017-ENER/SCFI-2012	Compact fluorescent lamps with integrated ballast	Energy efficiency and safety requirements: Limits and test procedures
NOM-018-ENER-2011	Thermal insulation material for buildings	Characteristics, limits and test procedures
NOM-019-ENER-2009	Mechanised tortilla machines	Thermal and electric efficiency: limits, test

		procedure and marking
NOM-020-ENER-2011	Buildings, building envelope of residential buildings	Energy efficiency
NOM-021-ENER/SCFI-2008	Room air conditioners (window type)	Energy efficiency, safety requirements: limits, test procedures and labelling
NOM-022-ENER/SCFI-2014	Self-contained commercial refrigeration appliances	Energy efficiency and safety requirements: limits, test procedures and labelling
NOM-023-ENER-2010	Room air conditioners (split type)	Energy efficiency: limits, test procedure and labelling
NOM-024-ENER-2012	Glass and glazing systems for buildings	Thermal and optical characteristics: labelling and test procedures
NOM-025-ENER-2013	Gas household cooking appliances	Thermal efficiency: test procedures and labelling
NOM-028-ENER-2010	Lamps for general use (incandescent, halogen, fluorescent)	Energy efficiency: limits and test procedures
NOM-030-ENER-2012	Integrated LED lamps for general lighting	Energy efficiency: limits and test procedures
NOM-031-ENER-2012	LED luminaires for street lighting and lighting of public outdoor areas	Energy efficiency: specifications and test procedures
NOM-032-ENER-2013	Standby electric power of equipment and appliances	Limits of electric power: test procedures and labelling
NOM-163-SEMARNAT-ENER-SCFI-2013	CO_2 emissions and fuel efficiency of automobiles	CO_2 emissions and fuel efficiency corporate average standards

Source: http://www.conuee.gob.mx/wb/Conuee/normalizacion_

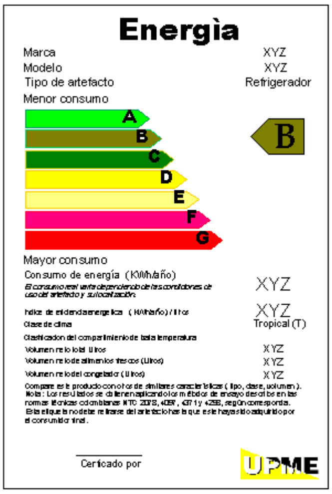
Figure 1: Energy efficiency labels in Mexico and in Andean Countries



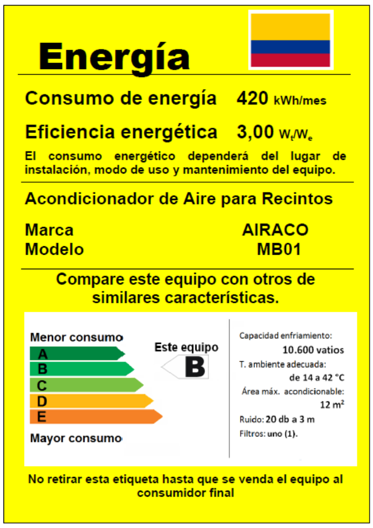
Mexico
Room Air Conditioner (NOM-021- ENER/SCFI-2008)

Venezuela
Refrigerator (COVENIN 3235:1999)

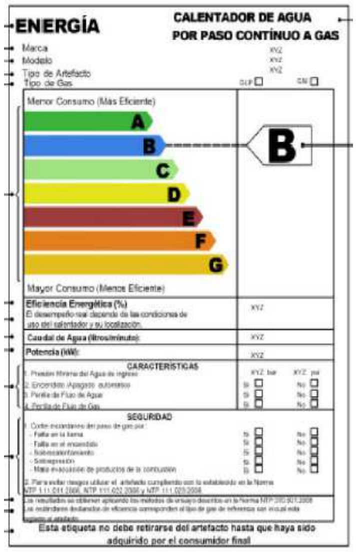
Venezuela
Air conditioner (Technical Regulation N° 071 November 2012)



Colombia
Refrigerator (old – NTC 5020:2002)



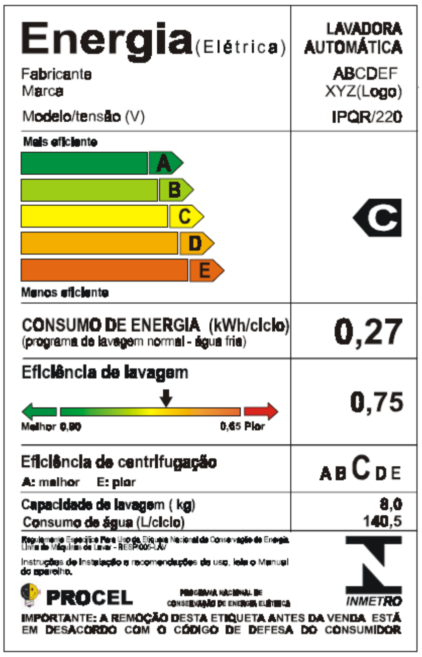
Colombia
Room Air Conditioner (new – RETIQ, draft June 2014)



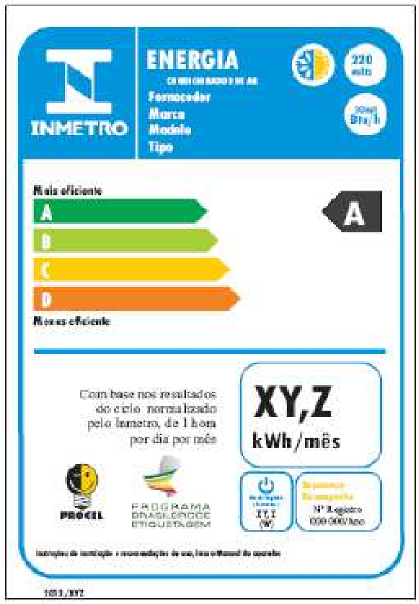
Peru
Gas Instantaneous Water Heater (Draft Technical Regulation, July 2011)

Figure 2: Energy efficiency labels in Brazil and in other Southern Cone countries

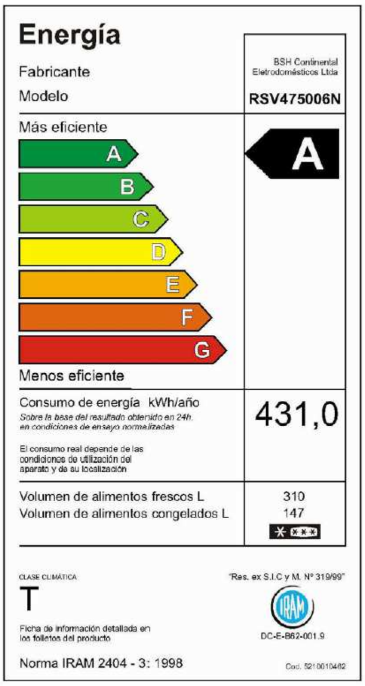
Brazil
Refrigerator (RESP/001-REF Ed. 1 December 2005)



Brazil
Automatic washing machine (RESP/005-LAV Ed. 1, Rev. 1 July 2005)

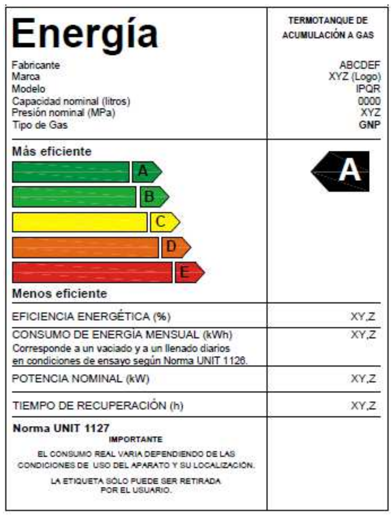


Brazil
Air conditioner (Portaria N° 410 August 2013)



Argentina
Refrigerator (IRAM 2404-3:1998)

Chile
Three Phase Squirrel Cage Electric Induction Motor (NCh 2582-2.Of2007)



Uruguay
Gas Storage Water Heater (UNIT 1127:2008)

Global Comparison of Standards and Labels

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Abstract

The global landscape of test procedures and energy efficiency metrics can seem complex and impenetrable. Policymakers can use international comparisons of energy performance requirements and product coverage to better inform decisions about energy performance standards and energy labels (S&L), thereby enabling more stringent policies. However, the current lack of comparability of S&L among economies can lead regulators to set more conservative efficiency requirements than they might if they could easily translate or adapt other economies' more stringent policies in their own policy terms.

This paper presents the largest and most comprehensive comparison of energy standards and labels[1] ever compiled, covering nine major economies and more than 100 products across eight different product areas. Data collected includes over 400 minimum energy performance standards (MEPS) and energy label regulations including their performance requirements, label thresholds, and the test procedures and energy efficiency metrics these are based on.

Energy performance regulations are built on a series of interconnected parts, each defining one building block for energy performance requirements and energy labels, and each one affecting the comparability of these policies. Based on the information collected, the analysis of comparability and expert opinion, the potential for (further) alignment of test procedures and efficiency metrics has been assessed. Of the products assessed, only 23% have test procedures which are aligned, of which 4 (5%) also have efficiency metrics aligned. The remaining 77% have no test procedure alignment.

In all cases, there is some potential for alignment, although that seems limited to components of test procedures in some cases. Full test procedure alignment appears possible for 27 more products, and alignment of efficiency metrics for 24 more products. Not every opportunity for greater alignment should be pursued. For globally traded products, similar products are used worldwide and alignment helps by saving regulators time and money, opening markets for trade, and lowering costs for consumers. For products with more local specifications, alignment may not produce the same benefits since governments must ensure that policies apply to local conditions. Substantial differences in climate conditions, energy prices, product ownership, and product usage patterns may lead to different energy and economic assessments for different countries.

Introduction and overview

The global landscape of test procedures and energy efficiency metrics can seem complex and impenetrable. Policymakers can use international comparisons of energy performance requirements and product coverage to better inform decisions about energy performance standards and energy labels (S&L), thereby enabling more stringent policies. However, the current lack of comparability of S&L among economies can lead regulators to set more conservative efficiency requirements than they might if they could easily translate or adapt other economies' more stringent policies in their own policy terms.

S&L policies are built on a series of technical foundations: product definitions, test procedures, efficiency metrics, and performance levels. Policymakers can increase alignment of product policies by improving the alignment of any of these building blocks.

Not every opportunity for greater alignment should be pursued. For globally traded products, similar products are used worldwide and alignment helps by saving regulators time and money, opening markets for trade, and lowering costs for consumers. For products with more local specifications, alignment may not produce the same benefits since governments must ensure that policies apply to local conditions. Substantial differences in climate conditions, energy prices, product ownership, and

1 Standards and labels, or S&L, is used as a collective term for minimum energy performance standards ("MEPS") and energy efficiency labels ("labels").

product usage patterns may lead to different energy and economic assessments for different countries.

This paper is based on a study[2] conducted by CLASP and The Policy Partners which represents the largest and most comprehensive comparison of minimum energy performance standards (MEPS) and energy labels ever compiled. It covers nine major economies—Australia, China, the European Union, India, Indonesia, Mexico, Russia, South Africa and the United States— and more than 100 products across eight different product areas. The full report of the study is available at http://www.clasponline.org/igc

Alignment by Product

International efforts over the past years, including via the Super-efficient Equipment and Appliance Deployment Initiative (SEAD) Initiative and IEC and ISO work, have focused largely on improving the alignment of existing test procedures and developing new test procedures.

Comparatively little work on the development of common energy efficiency metrics has been done, although regulators have sometimes aligned these without specific international efforts. Some test procedures, such as the one for electric motors, have developed to include efficiency metrics and a scale of product energy efficiency levels or tiers within the international test procedure. More commonly, however, efficiency metrics are developed separately within each economy, even if the test procedure is aligned internationally.

Figure 1. Alignment by product area

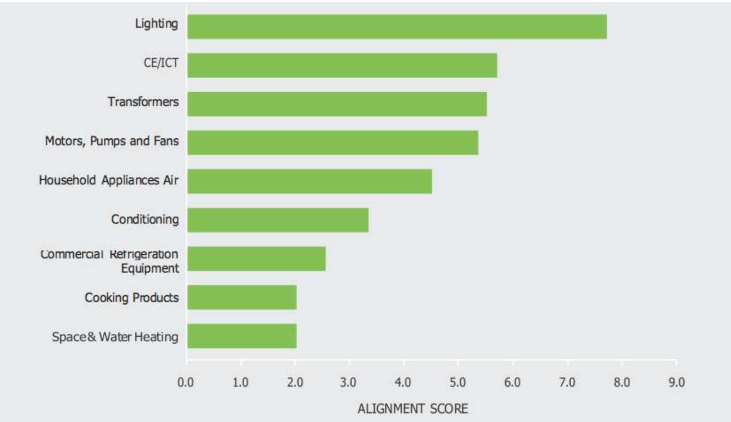

Figure 1 shows the level of alignment in each product area, comparing the number of aligned test procedures and efficiency metrics with the total number of products and the total number of regulated products in each area.

Differences in the level of alignment between product areas at least partially reflect the level to which products them- selves are internationally comparable.

Products that are globally traded and the same all over the world have higher alignment scores: lighting, consumer electronics (CE)/information and communication technology (ICT), transformers, and motors. Products with lower alignment scores often have larger regional differences in their design, usage, and characteristics: air conditioners, cooking products, and space and water heating

[2] Improving Global Comparability of Appliance Energy Efficiency Standards and Labels, The Policy Partners, September 2014. The study was produced for the Collaborative Labeling and Appliance Standards Program (CLASP) by Frank Klinckenberg, Mia Forbes Pirie and Laure McAndrew of The Policy Partners, May 2014. Able support was provided by Laya Taheri (The Policy Partners), Kevin Lane (Kevin Lane Oxford), Steven Beletich (Beletich Associates), Hugh Falkner (Atkins), Lloyd Harrington (Energy Efficient Strategies), Keith Jones (Digital CEnergy Australia) and Winton Smith (Puddle Consultancy).

products. In the middle of the spectrum, household appliances can be fairly easily converted among different regulations: These products have larger regional differences but a long history of energy performance regulation, so the impact of different regulations on their performance is by now better known.

Regional Alignment of Regulations

Figure 2. Alignment of test procedures and efficiency metrics by economy

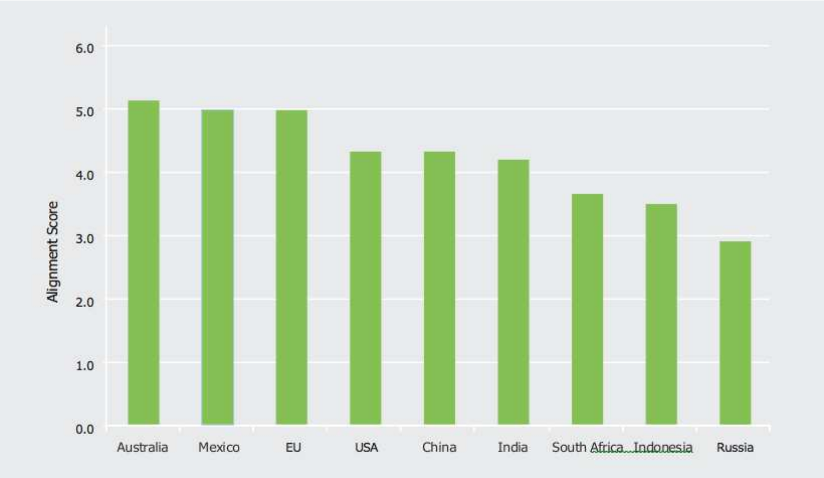

Figure 2 illustrates to what extent economies have aligned their regulations (MEPS and labels).

Alignment of test procedures and efficiency metrics varies between countries. Weighted by the number of regulations in place, Australia, Mexico and the EU show the highest levels of alignment within the economies included in this study. The US, China and India all show a similar slightly lower level of international alignment.

For Australia and Mexico, high alignment scores seem to be the result of a deliberate policy choice: in Australia's case, to align with the most appropriate international standard for its economy; in Mexico's case, to mainly copy (sometimes older) US regulations. The EU typically tackles products that have not previously been regulated elsewhere, thus setting an international benchmark for testing and evaluating efficiency for those products that is later adopted by other economies. A similar process applies to the US, although probably more limited to ICT products, for which US ENERGY STAR specifications seem to set the example for how to measure and rank energy performance.

Low alignment scores seem to be associated with uncertainty about S&L policies. Russia's low ranking is largely explained by the confusing state of its S&L, with many outdated Soviet-era standards in place with unclear legal status, and many new regulations possibly, but not certainly, in the process of being aligned with primarily EU requirements. Indonesia's and South Africa's scores are influenced by most of their S&L being under development and uncertainty about which test procedures and efficiency metrics will be applied.

In all economies, less than half of all regulations are fully aligned internationally. Australia, with its policy of international alignment, shows fully aligned test procedures and efficiency metrics for 14 of its 36 regulated products (included in this analysis), and Mexico, with its policy to align with the US, for 9 out of 22 analyzed regulations.

All economies, with the exception of Mexico, show more alignment in test procedures than in efficiency metrics. Whereas international test procedures often seem to provide a suitable way of measuring energy consumption under standardized conditions, efficiency metrics are more often adapted, probably to reflect different national circumstances such as climatic conditions or usage patterns.

Although there seems to be a movement towards using internationally aligned test procedures in all economies, efficiency metrics seem to be drifting further apart. For example, many economies are switching the metric for air conditioners from energy efficiency ratios (EERs) to seasonal energy efficiency ratios (SEERs). This incorporation of climatic conditions (which vary globally) appears to be leading to a divergence in S&L, despite convergence to a single internationally agreed test procedure.

Who's ahead in S&L development?

Product Coverage

The EU and the US are clearly ahead in regulating energy-using products (of the economies and products included in this analysis) with 67 and 70 products regulated, respectively.1 Perhaps surprisingly, the EU leads in the number of MEPS, with regulations for 62 products, whereas the US has more energy labels than the EU. This is a reversal of earlier years in which the EU relied more on energy labels and the US relied more on MEPS. It should be noted that most US labels are ENERGY STAR endorsement labels, whereas most EU labels are categorical energy labels, China leads in the number of energy labels in place, with 42 products labeled.

S&L Ambition Levels

The ambition level of MEPS and labels could only be compared with some reliability for 25% (18 out of 72) of the products covered in the analysis, across household appliances lighting products, some CE/ICT products, some air conditioning products, and motors.

Table 1. Most ambitious S&L identified by economy for all products analyzed

	Most ambitious		Unique most ambitious	
Country	**MEPS**	**High Label**	**MEPS**	**High Label**
Australia	3	5	2	3
China (PRC)	2	3	1	1
European Union	9	9	8	8
India	-	1	-	-
Indonesia	-	-	-	-
Mexico	2	2	1	-
U.S.	5	1	5	-
Russia	-	-	-	-
South Africa	-	-	-	-

Across these comparable products, the EU stands out as the clear leader in S&L development. The EU has by far the largest number of MEPS as well as the most ambitious MEPS and energy labels for more than half the comparable S&L. Table 1 shows the number of most ambitious S&L for each economy (including those where the lead is shared with other economies), as well as the number of unique most ambitious S&L (where the lead belongs to that economy alone). [3]

The number of products covered by S&L has grown substantially in recent years. The main driver for this has been the extension of scope and ambition level of several S&L programs. The EU Ecodesign program is now covering more products and often has more ambitious performance requirements, for MEPS and labels, than any other program.

[3] Comparisons like these should be treated with caution. For example, if products are only labeled in one economy, those will not show up in a comparison between economies.

It is important to note that there are some important differences among economies that contribute to variations in policy coverage and stringency. For example, substantial differences in energy prices, product ownership, and product usage patterns lead to different economic assessments from country to country.

Methodology

The conversion factors contained in the study underpinning this paper were developed through four main tasks described in this section:

- Developing an inventory of MEPS and labels and the underlying test procedures and efficiency metrics in the 9 economies selected
- Assessing the energy performance levels across different economies
- Developing conversion factors
- Assessing the robustness of the conversion factors

Inventory of MEPS and labels in 9 economies

As a starting point, a complete overview of existing MEPS and energy labels in all selected economies (Australia, China, EU, India, Indonesia, Mexico, Russian Federation, South Africa, and US) was compiled. This included the energy performance levels required by those regulations and the test procedures and efficiency metrics on which performance levels are based. The existing CLASP Global S&L Database had recently been updated for all relevant economies except for the US. The US section of that database was updated and the overall database ordered by product groups.

Assessment of energy performance levels across different economies

The aim of this task was to compare product energy performance data across economies, even though that data is based on different test procedures and energy efficiency metrics. In order to do this, research was undertaken to determine which, if any, international test procedure was used as the basis for national energy performance data and which modifications to that test procedure, if any, had been made, as well as whether these are likely to have a significant effect on reported energy performance.

Product experts, working with country experts where interpretation or translation was needed, determined which international test procedures were used in an economy for energy performance data, which modifications had been made to that test procedure and how significant these are. They also determined the energy performance levels required by a specific standard, and the highest and lowest energy performance level on the scale of energy labels (single level for endorsement labels or marks), and described these levels in a standardized way. This information was added to the information from the CLASP Global S&L Database, and an overview table for use in impact calculations was developed.

Conversions between test procedures

In order to be able to compare energy performance data from one economy to another, it was necessary to be able to convert energy performance measurements or declarations from one set of test procedure and efficiency metrics to another one. Most national test procedures are based on a limited set of international ones, sometimes with modifications, and it was necessary to develop conversions between those international test procedures (and work out the impact of modifications, where relevant) for all product groups.

Available existing research was reviewed, including the work of the IEA 4E Mapping & Benchmarking (M&B) Annex, CLASP's Benchmarking analyses and scoping studies, the analysis done for the previous Harmonization Study and various product-specific studies to determine for which product groups suitable conversion factors were already in place. For other product groups, the international test procedures in use were determined. Those procedures were then analyzed focusing on how differences between procedures can affect measured energy performance and estimated conversion factors between procedures. All work for this task was subjected to a technical review.

For some products (e.g., machine tools), only one test procedure is operational and conversions are not needed, while for other products (e.g., walk-in cold rooms), differences are so large that estimating conversion factors was not feasible within the scope of this study. For those cases, the main option is working with the reported energy performance as is, setting aside the unknown impact of test procedure differences for the moment. For the majority of products, however, reasonably accurate conversion, if not precise at a single product level, were available or could be estimated for this study.

Assessing the robustness of the conversion factors

Two types of conversion factors were developed for this study: test procedure conversion factors, and energy performance metric conversion factors. The former (test procedure conversion factors) are the numbers by which the result from the test procedure (the regional test procedure) should be multiplied in order to convert it to the reference test procedure (which is often an international standard but not always). The latter (energy performance metric conversion factors) is the number by which the result from the national energy performance metric should be multiplied in order to convert it to the metric produced by the reference test procedure. It is often the same multiplier as is used to convert from the regional test procedure to the reference test procedure.

As previously mentioned, these conversion factors are not intended to be used for conversions on an individual product (model by model) basis but rather for comparative conversions between product types at a national level. Some product types have significantly different requirements for sub- types, in which conversions need to be derived for representative sub-types. Although this approach is a fair approximation of an average conversion for the product type overall, as intended with this study, it does not necessarily mean that this also provides an accurate conversion for individual models or all sub-types of products.

Conversion factors and reliability

Given the possibility of widely diverging levels of reliability for conversion factors, the expert team then evaluated the reliability of the conversion factors developed. As well as documenting potential issues with conversion factors, a indicator was used to clearly indicate how reliable the factors were for high-level comparisons of high volumes of products (not for individual products). Conversion factors were coded as follows:

- High level of confidence in the conversion factor: Converted results would be in the right ballpark, with expert assumption that results are within 10% from the indicated value.
- Medium level of confidence in the conversion factor: Converted results would broadly be in the right ballpark, with the potential for substantial outliers and the margin of error is larger. Expert assumption is that results are within 25% from the indicated value.
- Unreliable conversion factors: Converted results would be better than nothing, but may be substantially off. Expert assumption is that results could be more than 25% from the indicated value.
- In several cases, conversion factors are listed as not applicable (N/A), indicating there is insufficient information even for unreliable conversion factors.

Information about product MEPS, energy labels and conversion factors is included in the report underlying this paper (See section 6 for an overview and Annex 2: Product Fact Sheets, for more detailed descriptions)[4].

[4] http://www.clasponline.org/igc

Potential for test procedure and efficiency metrics alignment

Of the 72 products analyzed, less than 25% have aligned test procedures today, and only 4 products have aligned efficiency metrics. As Table 3 shows, there is the potential for over 60% of products to have aligned test procedures, with almost 40% of those having the potential for aligned efficiency metrics.

Table 3 presents the assessment of alignment potential per product for the 8 product areas covered in this analysis. The best potential for alignment of test procedures and efficiency metrics appears to be in the lighting products, CE/ICT, and motors, pumps and fans areas, and the best potential for test procedure only alignment is in the household appliances and cooking products areas.

PRODUCT		Possible for test procedure components	Possible for full test procedure	Possible for test procedure & efficiency metrics	Test procedure already aligned, possible for efficiency metrics	Test procedure & efficiency metrics already aligned	Test procedure, efficiency metrics & ranking already aligned	Test procedure, efficiency metrics, ranking & label already aligned
Household appliances	Small refrigerator		■					
	Small refrigerator-freezer		■					
	Medium refrigerator-freezer		■					
	Chest freezer		■					
	Clothes Washer	■						
	Combination Clothes Washer/Dryer	■						
	Clothes Dryer		■					
	Dishwasher	■						
Lamps	Lamp - Compact fluorescent				■			
	Lamp - Filament, non-directional			■				
	Lamp - Filament, directional			■				
	Lamp - HID high pressure sodium				■			
	Lamp - HID metal halide				■			
	Ballast - HID (all)				■			
	Lamp - Linear fluorescent			■				
	Ballast - Fluorescent			■				
CE/ICT	Television				■			
	Display				■			
	Simple Set Top Box (STB)	■						
	Complex Set Top Box (STB)	■						
	Computer							■
	Server	■						
	Imaging Machine							■
	External Power Supply				■			
AC	Room AC		■					
	Chiller	■						
	Central AC	■						
Space & Water heaters	Space heater - Electric			■				
	Space heater - Residential boiler gas	■						
	Space heater - Residential boiler oil	■						
	Space heater - Commercial boiler gas	■						
	Space heater - Commercial boiler oil	■						
	Space heater - Commercial furnace gas	■						
	Space heater - Commercial furnace oil	■						
	Space heater - CHP	■						
	Space heater - Heat pump	■						

	Space heater - Furnace oil							
	Space heater - Furnace gas							
	Water heater - Instantaneous gas							
	Water heater - Instantaneous electric							
	Water heater - Heat pump							
	Water heater - Storage electric							
	Water heater - Storage gas							
	Water heater - Solar							
	Water heater - Commercial boiler oil							
	Water heater - Commercial boiler gas							
CRE	Refrigerated Display Cabinet							
	Refrigerated Cabinet							
	Refrigerated Vending Machine							
	Walk-In Cooler & Freezer							
	Freezer							
	Ice Machine							
Cooking	Oven							
	Cook top/hob							
	Microwave oven							
	Rice cooker							
	Coffee maker							
Motors, Pumps & Fans	Medium 3-Phase General Purpose							
	Small 3-phase General Purpose							
	Generic pumps							
	Heat Pump Systems							
	Building Circulator							
	Pool							
	Dirty water							
	Agricultural							
	Cooktop/Fume Hood							
	Portable Fan							
	Industrial Blower							
	Ceiling Fan							
	Furnace/Duct Fan							
	Integrated Fan							
	Distribution transformer							
Total		**28**	**16**	**11**	**13**	**0**	**2**	**2**

Conclusions and Alignment Potential Overview

The analysis shows a wide range of alignment for test procedures and efficiency metrics in place: a few products have fully aligned test procedures and efficiency metrics, even including aligned efficiency levels (such as electric motors) or aligned labels (such as some ICT products). Most products, however, have virtually no alignment of test procedures.

For all products, there is some potential for harmonization, although in some cases that seems limited to components of test procedures. For many heating and cooling products, for example, it may be possible to define common tests of product components or modes of operation; such an approach has recently been used successfully for ISO standards for pump systems. In other cases, such as household refrigerators, fully aligned test procedures seem to be achievable.

Efficiency metrics, however, appear to be much harder to align than test procedures. Alignment of efficiency metrics first requires that test procedures are aligned. In addition, local usage characteristics must be similar enough for a single efficiency metric to acceptably describe what constitutes energy performance for a product globally.

In many cases, alignment of efficiency metrics may even be decreasing. A good example of this is in air conditioning, where virtually all economies have aligned to the same international test procedure for testing product performance, but then use quite different efficiency metrics to assess energy performance. In addition to counteracting the progress being made via test procedures or improving product comparability, this also creates a barrier for the transfer of energy-efficient technologies between economies with different metrics. It is important to recognize, however, that locally tailored efficiency metrics can be important to ensure that MEPS and energy labels are representative of actual usage in an economy.

Table 4. Alignment potential per product

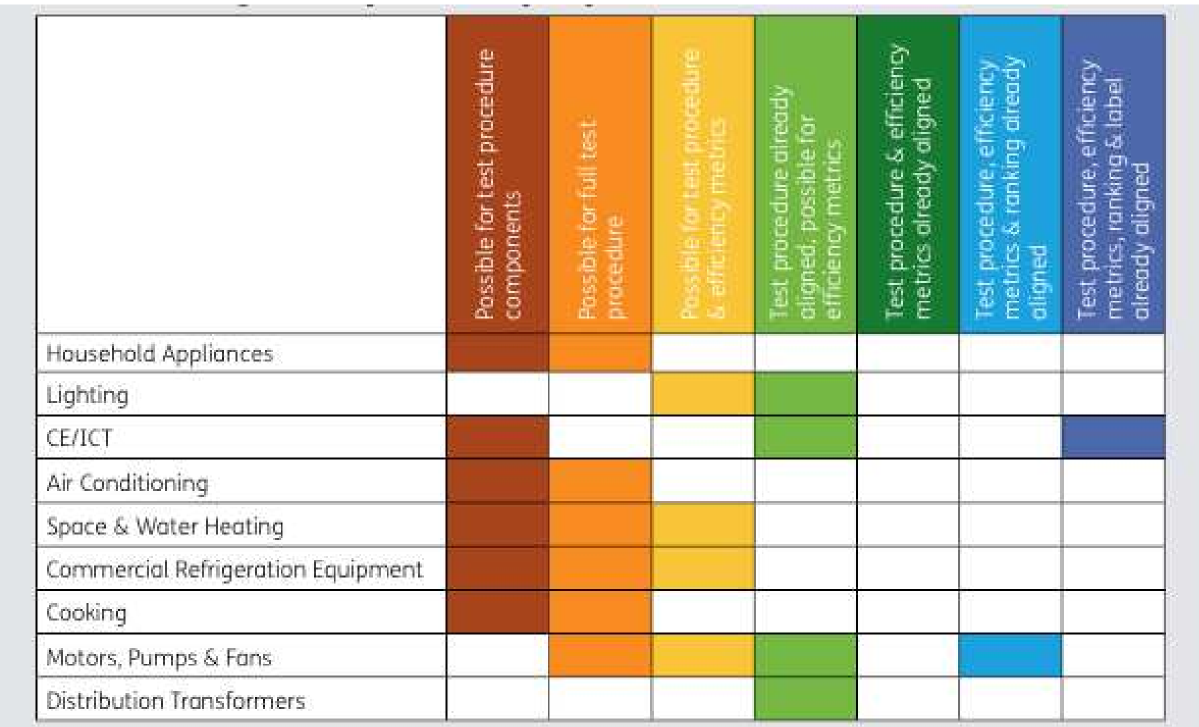

Table 4 presents the assessment of alignment potential per product for the 8 product areas covered in this analysis. The best potential for alignment of test procedures and efficiency metrics appears to be in the lighting products, CE/ICT, and motors, pumps and fans areas, and the best potential for test procedure only alignment is in the household appliances and cooking products areas.

Figure 3. Potential for alignment of test procedures and efficiency metrics

As Figure 3 shows, less than 25% of the 72 products analyzed have aligned test procedures today, and only 4 products have aligned efficiency metrics. There is the potential for over 60% of products to have aligned test procedures, with almost 40% having the potential for aligned efficiency metrics.

Test procedures and efficiency metrics alignment can be complicated by existing national procedures and metrics. Many product designs are tailored to national procedures and metrics, in which case a switch to a different test procedure or efficiency metric may result in substantial shifts in the energy efficiency rankings of existing products in an economy. In addition, existing national test procedures and efficiency metrics may reflect product designs that differ substantially between economies (as is the case for many heating products), or be representative of specific local usage patterns or climatic conditions not found elsewhere (as, for example, for many cooking products). A case- by-case assessment is needed to determine the expected benefits and the potential for the development of internationally aligned test procedures and efficiency metrics.

Potential Impact of Lighting and Appliance Efficiency Standards on Peak Demand: The Case of Indonesia

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Abstract

By now, the value of lighting and appliance energy efficiency standards to reduce power plant fuel inputs, thereby saving money, reducing harmful pollution, mitigating climate change and enhancing energy security is well-known. As important as these benefits may be to developing country governments, even more critical in their view may be the reduction of peak demand, since power shortages (due to insufficient capacity) damage economic productivity and generation capacity increases commit scarce capital to power plant construction that could be used toward other important development goals.

This paper uses LBNL (Lawrence Berkeley National Laboratory)'s BUENAS (Bottom-Up Energy Analysis System) model to forecast demand reductions from energy efficiency in a major developing country – Indonesia. Indonesia was chosen for its tropical climate (making cooling important to peak load) and because its level of development which suggests rapid growth of appliance uptake over the next two decades. The model considers future demand growth for 10 separate residential electrical end uses, three commercial building end uses, and considers industrial electricity in the aggregate. The model then combines the total electricity demand by appliance in each year with end use demand curves for each using data from Indonesia (if possible) and areas of similar climate. The resulting analysis finds that peak load may increase 3 times in Indonesia over the next 20 years in the business-as-usual case, primarily driven by space cooling with an important component from lighting and refrigerators. Applying BUENAS efficiency scenarios of cost-effective potential and best available technology indicates a potential peak load reduction of 13% and 37% in 2030, respectively.

Introduction

By now, the value of lighting and appliance energy efficiency standards to reduce power plant fuel inputs, thereby saving money, reducing harmful pollution, mitigating climate change and enhancing energy security is well-known. As important as these benefits may be to developing country governments, even more critical in their view may be the reduction of peak demand, since power lshortages (due to insufficient capacity) damage economic productivity and generation capacity increases commit scarce capital to power plant construction that could be used toward other important development goals.

Over the past decade, Lawrence Berkeley National Laboratory (LBNL) has developed two main modeling tools to provide ex ante analysis of the impacts of minimum energy performance standards (MEPS) for specific equipment types in specific countries. These are the Policy Analysis Modeling System (PAMS[1]) and the Bottom-Up Energy Analysis System (BUENAS). These models are similar in that they combine assessments of baseline efficiency with regulated efficiency improvements, costs and projections of equipment markets (sales forecasts) in order to yield energy, environmental and financial impacts on an annual basis to a long-term horizon (usually 2030). However, while PAMS is a single-appliance model with an emphasis on cost-effectiveness metrics, BUENAS covers multiple countries and products simultaneously.

Initial development of BUENAS was supported by CLASP. It has since been supported by multiple sponsors and is currently the main modeling platform for the SEAD (Super Efficient Appliance Deployment) initiative. BUENAS quantifies savings for minimum energy performance standards (MEPS) recently passed by the 15 SEAD member economies [1], as well as potential savings under scenarios such as the most stringent cost-effective MEPS, and adoption of best available

[1] More information available at https://ies.lbl.gov/project/policy-analysis-modeling-system

technologies [2]. Until now, BUENAS has measured impacts in terms of total energy saved in TWh or PJ and the related financial impacts and greenhouse gas emissions in MT CO_2.

This paper describes an extension of the BUENAS model to evaluate growth of peak electricity demand and potential reductions from energy efficiency policies. These quantities are most closely related to electricity generation capacity, and therefore the amount of capital investments required by a rapidly developing economy for power plant construction. In order to demonstrate this capability, we model peak load in a major developing country – Indonesia. Indonesia was chosen for its tropical climate (making cooling important to peak load) and because its level of development which suggests rapid growth of appliance uptake over the next two decades. The model considers future demand growth for ten separate residential electrical end uses, three commercial building end uses, and considers industrial electricity in the aggregate.

Under the SEAD initiative, LBNL is collaborating with the Indonesian Ministry of Energy and Mines Resources in order to improve and validate the BUENAS model developed for Indonesia. While the current analysis focuses on Indonesia as a case study for demonstrating peak demand modeling capability, a more accurate forecast of end use demand and energy savings potential will be available as a result of the upcoming collaboration.

Methodology

The extension of the BUENAS energy demand and savings model to produce estimates of peak load requirements and reductions requires combination of average annual energy demand with the hourly load profile of energy use. In order to draw meaningful conclusions, these must be specified for each end use individually, since the time of use, or *load profile* varies significantly between end uses. Furthermore, projections of total future supply requirements necessitate relatively comprehensive coverage across end uses and sectors. Therefore, while the emphasis of the study is on the contribution from residential appliances, all major electricity-consuming sectors are covered.

BUENAS Indonesia Model

The main objective of the BUENAS model is to provide sufficient detail and accuracy for quantitative assessment of policy measures such as appliance energy efficiency standards and labeling (EES&L) programs. In most countries where energy efficiency policies exist, the initial emphasis is on household appliances and lighting. Often, equipment used in commercial buildings, particularly heating, air conditioning and ventilation (HVAC) is also covered by EES&L programs. In the industrial sector, standards and labeling generally covers electric motors, distribution transformers and lighting. Recently, though, a few more types of industrial equipment are covered by some programs, and there is a trend toward including more of them.

BUENAS projects energy consumption by end use from a 2010 base year to 2030. The strategy of the model is to first project end use activity, which is driven by increased ownership of household appliances, floor space in the commercial sector and economic growth in the industrial sector. For most major appliances, the stock of appliances is projected from unit sales data. In cases where these data are not available, ownership rates can be modeled through econometric diffusion equations developed by the authors [3]. Electricity consumption or intensity of the appliance stock is then calculated according to estimates of the baseline intensity of the prevailing technology. Finally, the total final energy consumption of the stock is calculated by modeling the flow of products into the stock and the efficiency of purchased units, either as additions or as replacements of old units according to equipment retirement rates. The high efficiency or “policy” scenario is created by the assumption of increased unit efficiency relative to the baseline starting in a certain year. For example, if the average baseline unit energy consumption (UEC) of new refrigerators is 450 kWh/year, but a MEPS taking effect in 2015 requires a maximum UEC of 350 kWh/year, the stock energy in the policy scenario will gradually become lower than that of the base case scenario due to increasing penetration of high-efficiency units under the standard. By 2030, the entire stock will generally be impacted by the standard. More details on the BUENAS methodology are given in [2].

End-use Load Profiles

In this study, the average daily load curve for Indonesia is modeled using appliance and sector specific load profiles. End use load profile data generally originates from time of use surveys or metering and vary by climate, season and customer type. While these data are becoming more common, they are not available for every end use in every country. Wherever possible, this study used load profiles specific to Indonesia. In the case that these were not available, we used load profiles from other countries and locales with a similar climate to Indonesia, such as Malaysia and India. Table 1 provides the list of load profiles used in this study by end-use, sector, source, and region. Since the climate in Indonesia is characteristically tropical with abundant rainfall, high temperatures and high humidity throughout the country, only one characteristic load profile was considered for each end use and/or sector. Standby power losses are assumed not to vary by geography, and are estimated from a European Commission source.

Table 1 End-use load profiles used in this study

End-Use	Sector	Source	Geographical Region
Lighting	Residential	[4]	Indonesia
Lighting	Commercial	[5]	Gujarat, India
Air conditioners	Residential	[6]	Kansai, Japan
Air conditioners	Commercial	[5]	Gujarat, India
Televisions	Residential	[5]	Gujarat, India
Refrigerators	Residential	[7]	India
Refrigerators	Commercial	[5]	Gujarat, India
Fans	Residential	[8]	Jahor Bahru, Malaysia
Rice cookers	Residential	[9]	Osaka City, Japan
Other Residential*	Residential	[9]	Osaka City, Japan
Standby Power	Residential	[10]	Europe
Industry	Industrial	[11]	Indonesia

** Other Residential represent kettle and clothes washer.*

Figures 1-3 show the normalized profiles used in this study for the residential, commercial and industrial end uses respectively. The residential sector is built up from individual end uses. The “other residential” includes kettles, electric irons, and clothes washers. Individual end uses are not defined for the industrial sector, which has a relatively flat load profile compared to the other sectors. In this case, the total sector load profile is taken directly from Indonesian data. For comparison, each load profile is normalized so that the average load on each curve is equal to one. The normalized load for each hour is multiplied by the average hourly end use energy consumption in order to get total end use load by hour on a typical day. The calculation is as follows:

Load at t (MW) $_{(end\ use)}$ = ***Average hourly energy consumption (MW)*** $_{(end\ use)}$ × ***Load on normalized curve at t*** $_{(end\ use)}$

Average hourly energy consumption (MW) $_{(end\ use)}$ **=** ***Annual energy consumption (TWh)*** $_{(end\ use)}$ ***/ 8760[2]/ 10***^{6}

[2] 8760 is the number of hours in a year

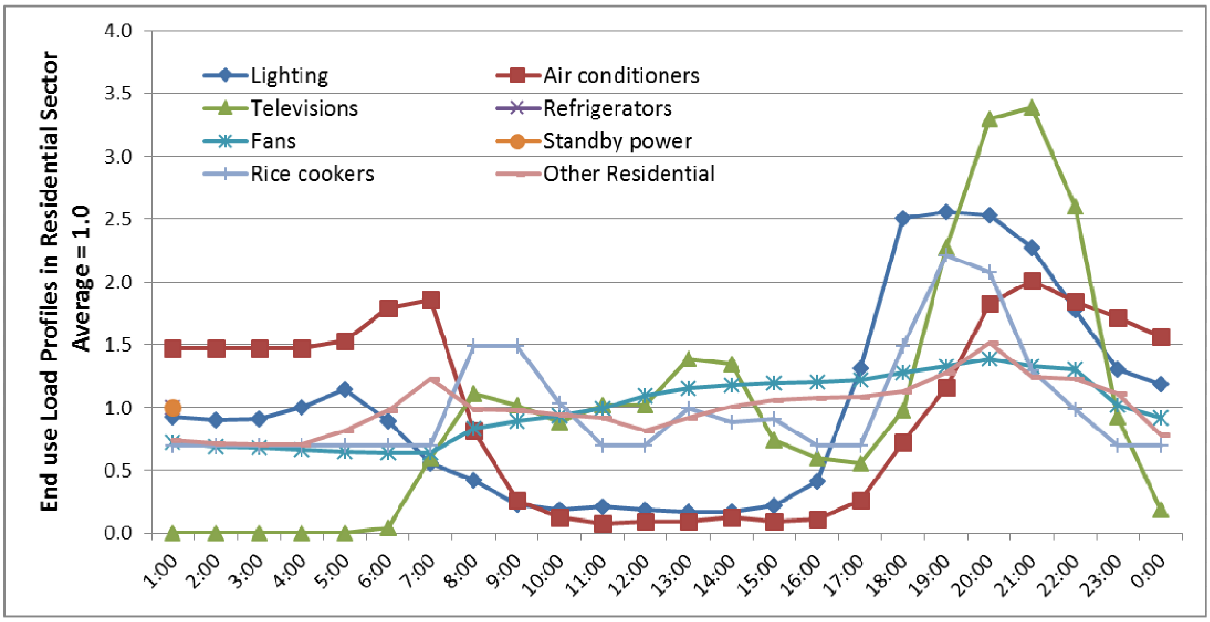


Figure 1 Residential sector Load Profiles Normalized to the average = 1.0

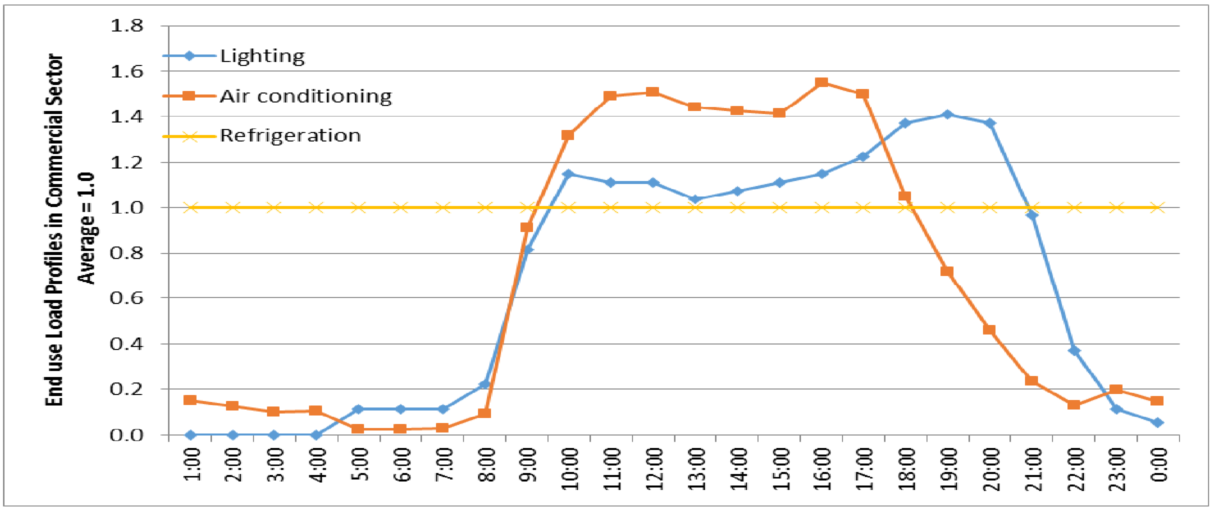


Figure 2 Commercial sector load profiles normalized to the average = 1.0

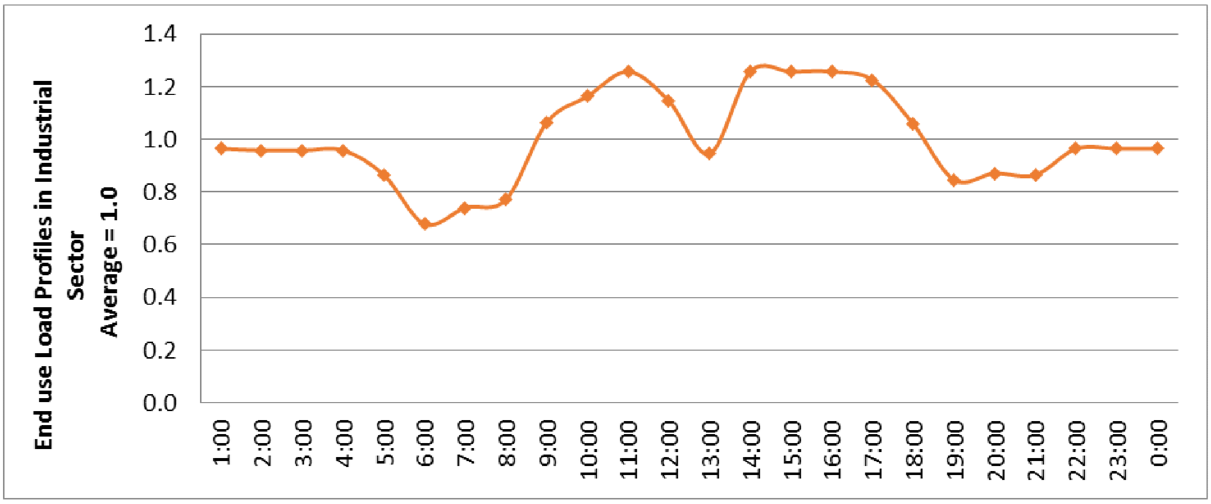


Figure 3 Industrial sector load profiles normalized to the average = 1.0

Business as Usual (BAU) Projections

The population of Indonesia in 2010 was 240.7 million, making it the world's fourth most populous country. About half of the population still lives in rural areas [12]. The UN predicts that 60.3% of the population will be urbanized by 2025 [13]. It is assumed that the population in Indonesia increases over time with an average annual growth rate of 1% (see Figure 4). In the periods past 2010, the gross domestic product (GDP) per capita increases at an assumed average growth rate 3.9% and reaches to 8837 US$(2007) in 2030. Table 2 provides the household size and electrification ratios assumed in this study. Household size decline 0.8% and electrification ratio increases 1.8% per year as average until 2030.

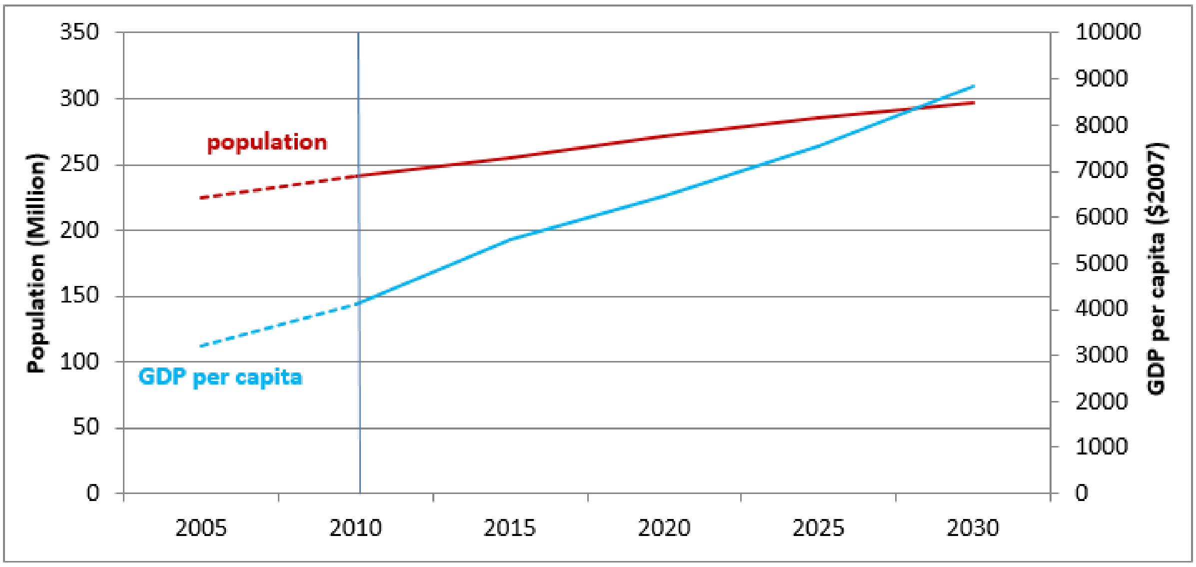


Figure 4 Population and GDP growth modeled in the study
(Source: [13] for population growth, [14] for GDP per capita growth)

Table 2 Household size and electrification rate modeled in the study

	2010	2015	2020	2025	2030
Household size	3.9	3.73	3.63	3.49	3.32
Electrification rate	70%	79%	90%	97%	100%

When possible, stock of appliances in the residential sector are modeled by a stock turnover analysis using historical sales data (Euromonitor [15], BSRIA [16]) combined with appliance lifetime estimates. Diffusion (ownership) levels for these years are then calculated by dividing the stock by the number of households in the country. Diffusion and stock are extrapolated to 2030 using BUENAS macroeconomic modeling, which uses GDP, electrification, urbanization, climate parameters and population as drivers.

Diffusion level of the equipment in this study are low in the base year, with the exception of ceiling fans and televisions For example, we find that only 31% of the households have a refrigerator in 2010, and luxury items like air conditioners is owned by a very small portion of the country (diffusion level of 8% in 2010). Even if the market is rapidly moving to LCD and LED flat screen televisions, we find that most of the households still own CRT televisions, which is the most inefficient television group in the market. The current low rates of appliance ownership (i.e., diffusion) coupled with high economic growth rates imply that Indonesia is poised for rapid growth in electricity demand, particularly in the residential sector. As can be seen, rapidly growing sales (driven by GDP and population) yields significant increases in the total number of appliances in the stock in residential sector in the medium and long term, especially for large appliances like refrigerators and air conditioners, as can be seen in Figure 5.

Figure 5 Projected diffusion (units per household) of residential appliances (2000-2030)

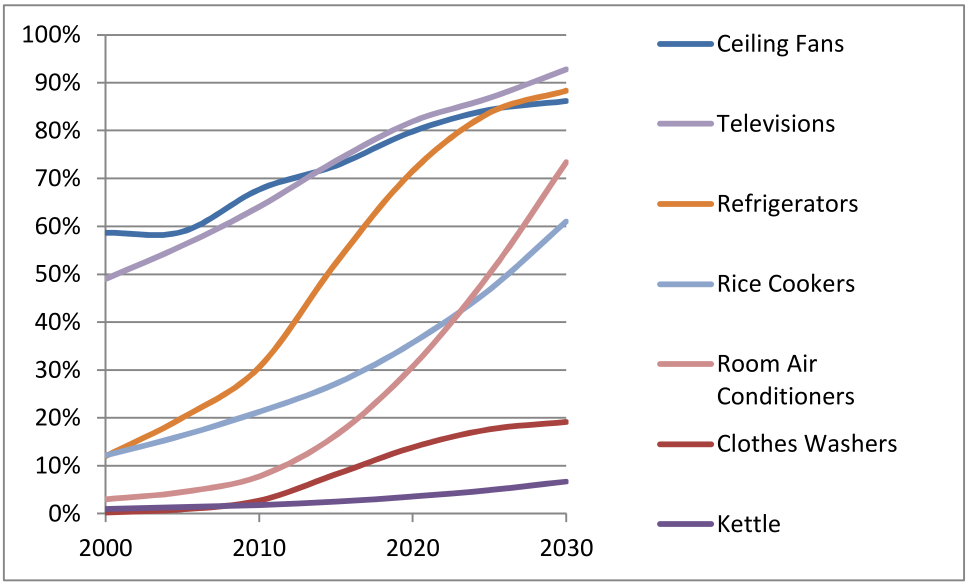


Table 3 shows the average unit energy consumption (UEC) of all appliances considered. Most of these UEC are based on proxies from other countries. For example, the UEC of a typical air conditioner in Indonesia has been taken from India given the similarities in climate and income. With this assumption, air conditioners consume almost 2.5 times more electricity than the next largest item, a refrigerator. Therefore, one could expect a large impact on electricity consumption and peak load with moderate increases in air conditioners ownership.

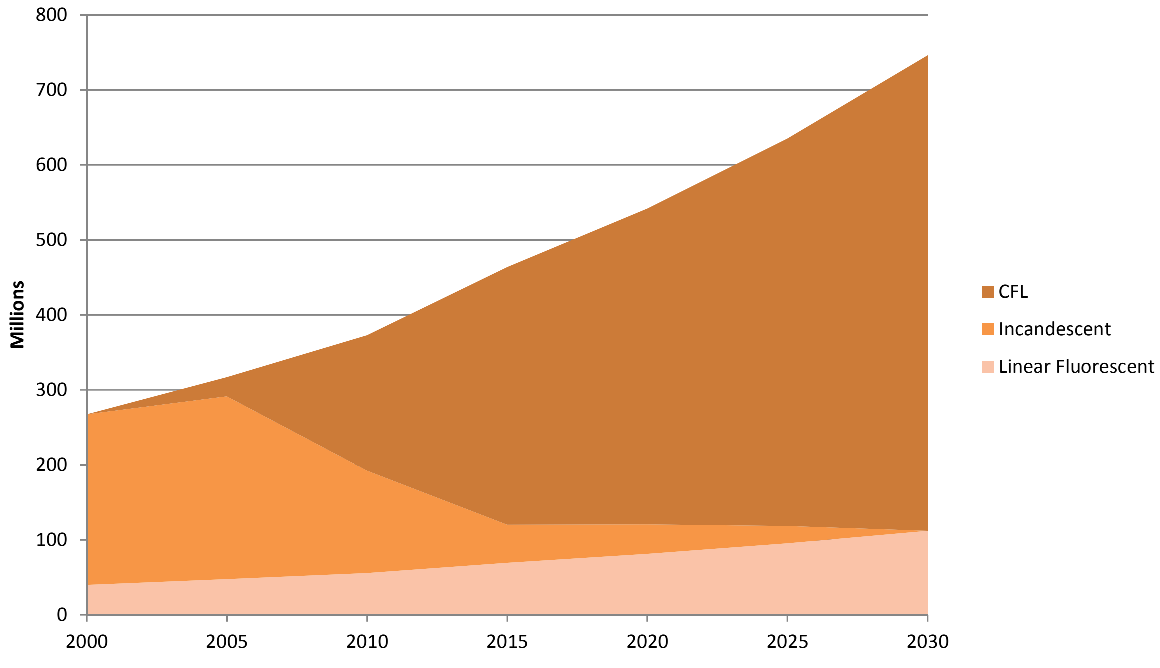
The BAU scenario assumes frozen efficiency with the exception of lighting (assumes a progressive phase-out of incandescent lighting by 2030) and televisions (assumes progressive efficiency improvements in CRT, LCD and plasma). In addition, we model two different types of refrigerators; direct cool refrigerator with 337 kWh/yr, frost-free refrigerator with 675 kWh/yr. Refrigerator capacity and efficiency is modeled with reference to the Indian market [7]. It is assumed that diffusion of frost-free refrigerators would be higher in Indonesia in the long term. Thus, the weighted average of UEC increases between 2010 and 2030 (see Table 3).

Table 3 Assumed UEC of appliances in the residential sector (kWh/yr)

	2010 UEC	2020 UEC	2030 UEC	Source
Air Conditioners	1,416			[7]
Refrigerator	574	618	650	[7]
Television				
LCD	233	53	53	[17]
CRT	192	176	176	[17]
Plasma	305	224	224	[17]
Fans	224			[18]
Clothes Washer	150			[19]
Rice Cooker	242			[19]
Kettle	216			[19]

Figure 6 shows the market share of different lighting types used in Indonesia between 2000 and 2030. Incandescent lamps, which are the most energy consuming lighting type has a very high share in 2005. However, its share gradually decreases and reaches zero in 2030. Unlike other appliances, sales data for lighting are not available. Therefore, diffusion rate projections for this end use are modeled econometrically (See [3]).

Figure 6 Lighting Stock by technology in the residential sector (BAU assumptions)



* CFL (Compact fluorescent lights)

We used BUENAS model to forecast end-use electricity consumption in the commercial sector for Indonesia [2].The end-use included in the commercial sector are lighting, space cooling and refrigeration. BUENAS bottom-up energy demand totals were then scaled up to match commercial electricity consumption in the base year.

For the industry sector, we assumed that electricity demand grows with growth in GDP.

We then apply the load curves by applying the method described above, and account for transmission and distribution losses of 9% [20]. and compare the peak load results with peak from national statistics and find that the modeled peak load (25.8 GW) is 4.4% higher than the realized peak load

(24.7 GW) in 2010 [21]. While the agreement between modeled peak load and actual peak is small, we caution against interpreting this agreement as an indication of very high precision. We would not expect exact agreement, in fact, because there are undoubtedly some end uses not captured by the model, such as small plug loads. On the other hand, since load is often not met, realized peak load is somewhat lower than peak demand. These compensating errors may contribute to the apparent agreement seen in results.

BAU Results

The daily load curve represents the total electricity consumption by all end use equipment in operation at any given hour. Development of Indonesia's average daily load curve between 2010 and 2030 is illustrated in Figure 7. Indonesia's modeled electricity demand at peak hour under BAU assumptions is projected to increase by 67% (to reach 43.0 GW) in 2020 and by 184% (to reach 73.1GW) in 2030, compared to 25.8 GW at 2010. Meeting this demand growth would require the addition of the equivalent electricity generation of 34 and 95 500-MW power plants in 2020 and 2030, respectively.

Figure 7 also shows the details of electricity consumption on load curve in 2010 by sectors and end uses. As can be seen, in 2010, peak load is mostly driven by residential lighting. Almost 25% of electricity at peak hour is used by lighting. In addition, televisions, which account for 14% of the peak load, and residential lighting together have almost same electricity demand at peak hour, compared to commercial and industrial sectors together (which account for 38% of the peak demand), in 2010.

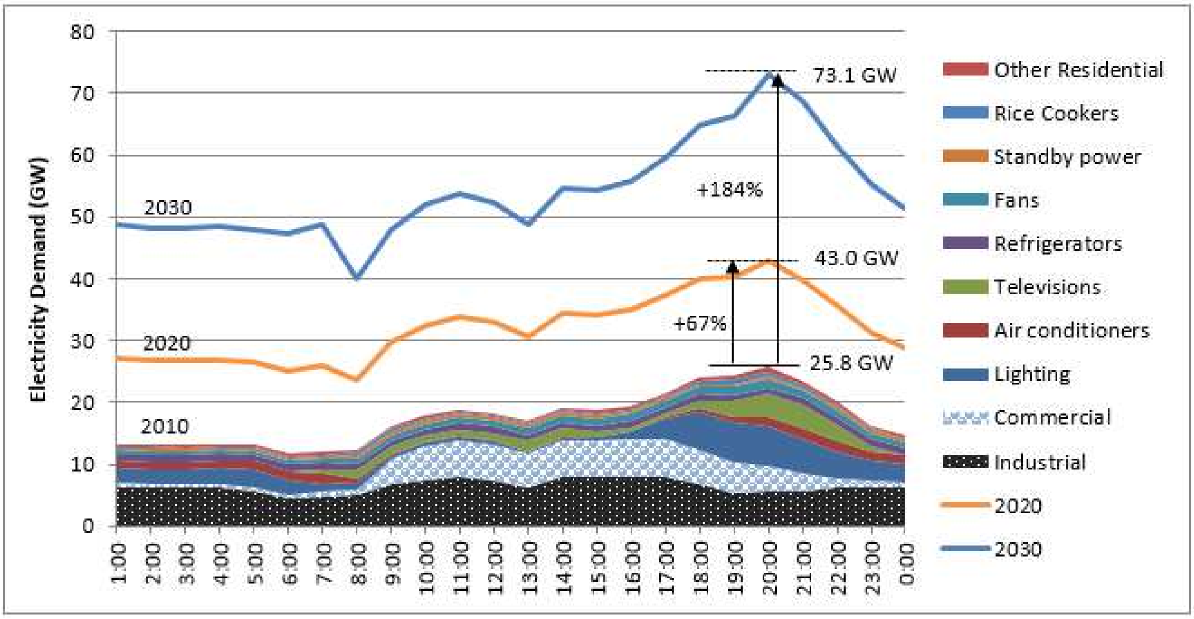


Figure 7 Development of Indonesia's average daily load curve in the BAU scenario between 2010 and 2030

Figure 8 shows the details of the load curve in 2030 in the BAU scenario. In 2030, the electricity demand at the peak is mostly distributed among residential air conditioners (29%), commercial and industrial sectors (18% and 20%), residential lighting and refrigerators (10% and 8%). As can be seen, the share of residential air conditioners, lighting, and refrigerators is larger than the share of commercial and industrial sectors at the peak in 2030. Particularly, contribution of air conditioners to peak load grows roughly five times between 2010 and 2030. Together with its high UEC levels, residential air conditioners have a large impact on peak load in 2030. On the other hand, the share of lighting at peak decreases, due to progressive phase-out of incandescent lamps.

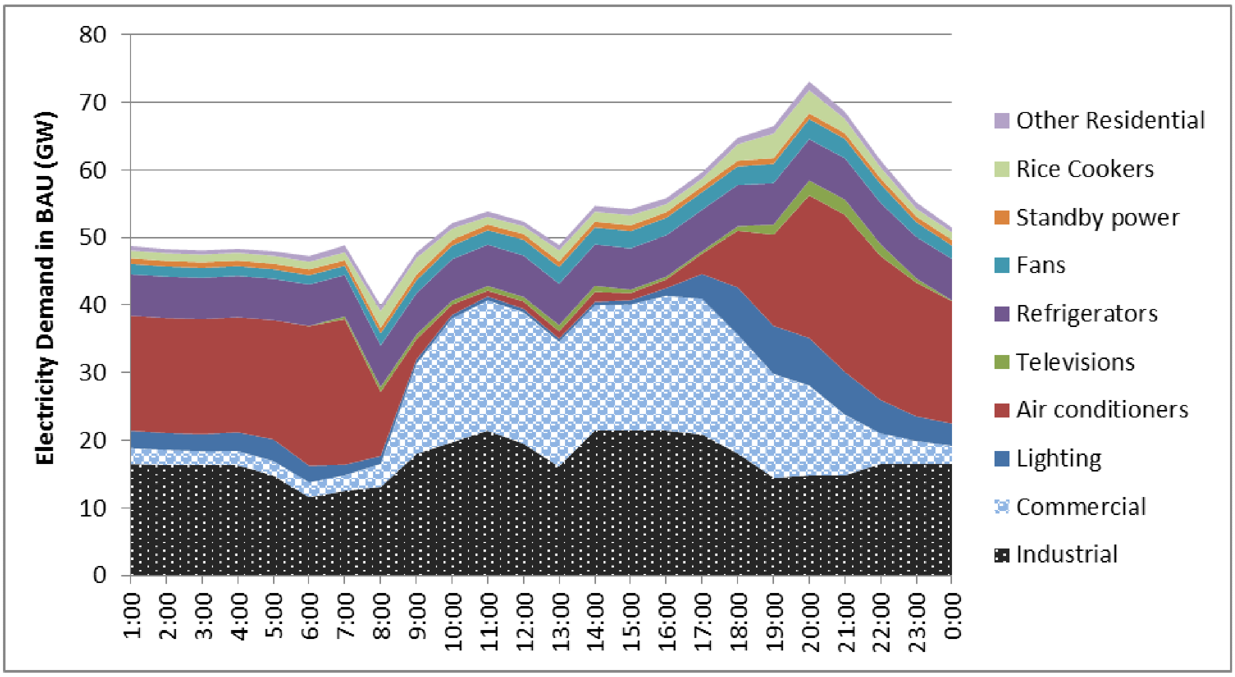


Figure 8 Indonesia average daily load curve in the BAU scenario in 2030 by end use and sector

High Efficiency Scenarios

Two efficiency improvement scenarios are analyzed within the scope of this study in addition to the *BAU*: namely, *CEP* and *BAT*. These scenarios are taken from [22] and [23].

The scenario assumptions on lighting and unit energy consumption of appliances are summarized in Table 4 and 5.

- The ***CEP* (Cost Effective Potential) scenario** takes into consideration efficiency targets that provide the maximum energy savings that result in a net benefit to the consumer (even with subsidized electricity tariffs). It is only available for the residential sector.
- The ***BAT* (Best Available Technology) scenario** evaluates the technical potential for energy efficiency afforded by the best technologies currently available on the market or designed from high efficiency components. It is only available for the residential sector end-uses, commercial lighting, air conditioners, and refrigerators.

Table 4 Lighting market shares in 2020 and 2030 considered in the scenarios

	BAU			CEP			BAT		
	2010	**2020**	**2030**	**2010**	**2020**	**2030**	**2010**	**2020**	**2030**
Incandescent	37%	7%	0%	37%	0%	0%	37%	0%	0%
CFL	48%	78%	85%	48%	85%	85%	48%	0%	0%
LED	0%	0%	0%	0%	0%	0%	0%	85%	85%
Linear Fluorescent Lamps	15%	15%	15%	15%	15%	15%	15%	15%	15%

Table 5 Unit energy consumption in BAU, CEP, and BAT scenarios in 2020 and 2030 (kWh/yr)

	BAU		CEP		BAT	
	2020	**2030**	**2020**	**2030**	**2020**	**2030**
Air Conditioners	1,416	1,4156	1,000	1,000	637	637
Refrigerators	618	650	345	370	117	117
Televisions						
LCD	53	53	53	53	14	14
CRT	176	176	N/A in CEP	N/A in CEP	N/A in BAT	N/A in BAT
Plasma	224	224	N/A in CEP	N/A in CEP	14	14
Fans	224	224	164	164	103	103
Clothes Washers	150	150	150	150	135	135
Rice Cookers	242	242	242	242	242	242
Kettles	216	216	216	216	216	216

Scenario Results

Due to the introduction of more energy efficient lighting, appliances and equipment, peak load increases more slowly in the *CEP* and *BAT* scenarios than in the BAU scenario. Between 2010 and 2030, Indonesia's peak load grows by 147% (i.e., to 63.6 GW) in the *CEP* scenario, and by 84% (i.e., to 47.3 GW) in the BAT scenario. These scenarios project a need for 76 and 43 large power plants, respectively, compared to 95 in the BAU scenario. These results indicate 19 and 51 fewer large power plants in the *CEP* and *BAT* scenarios.

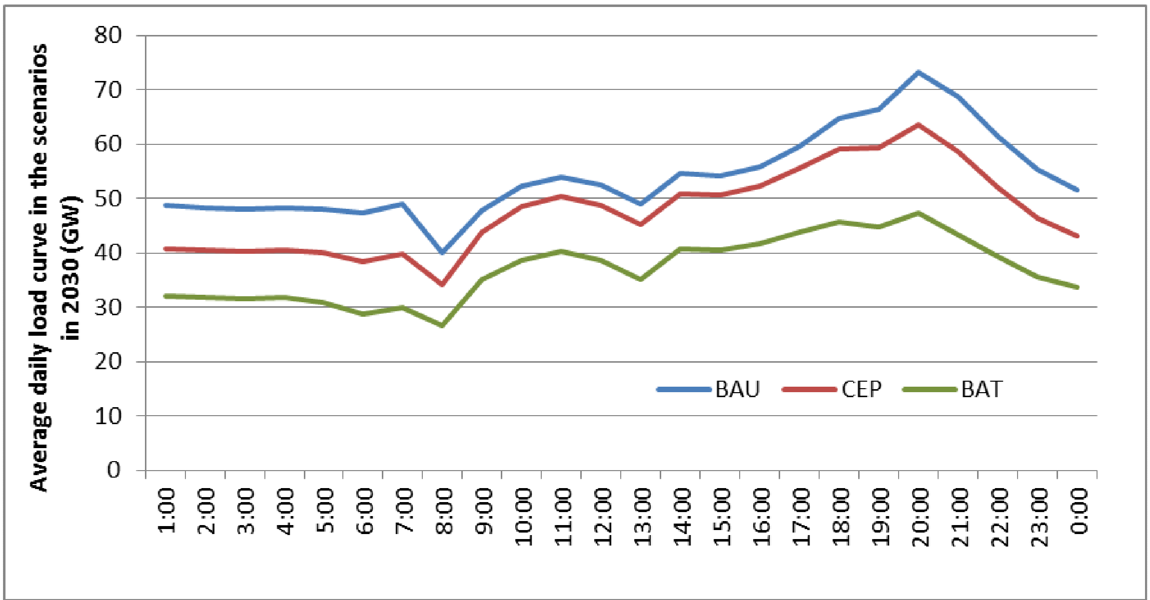


Figure 9 Indonesia average daily load curve in the scenarios in 2030

Figures 10 and 11 show the details of the energy savings in the *CEP* and *BAT* scenarios compared to the BAU scenario in 2030. Electricity demand at peak hour is reduced by 13% and 35% in the *CEP* and *BAT* scenarios, respectively, relative to *BAU*. Air conditioners and refrigerators are the end-uses that contribute most to the reduction of peak load (see Table 6). These end uses reduce the peak load by 8% (12 fewer large power plants) and 3% (5 fewer large power plants), respectively, in 2030, in the CEP scenario. In the BAT scenario, in contrast, 16% (23 fewer large power plants) and 6% (9 fewer large power plants) of the peak load reduction is from refrigerator and air conditioners, respectively, in 2030. In the BAT scenario, commercial sector also decreases the peak load 6% as a consequence of efficiency improvement in commercial lighting, air conditioners, and refrigerators.

The energy required for lighting is reduced significantly in both scenarios due to complete replacement of incandescent lighting by CFLs in the *CEP* scenario and by LEDs in the *BAT* scenario. Likewise, efficiency improvement of refrigerators and air conditioners in the *CEP* and *BAT* scenarios result in much lower energy demand from those end-uses.

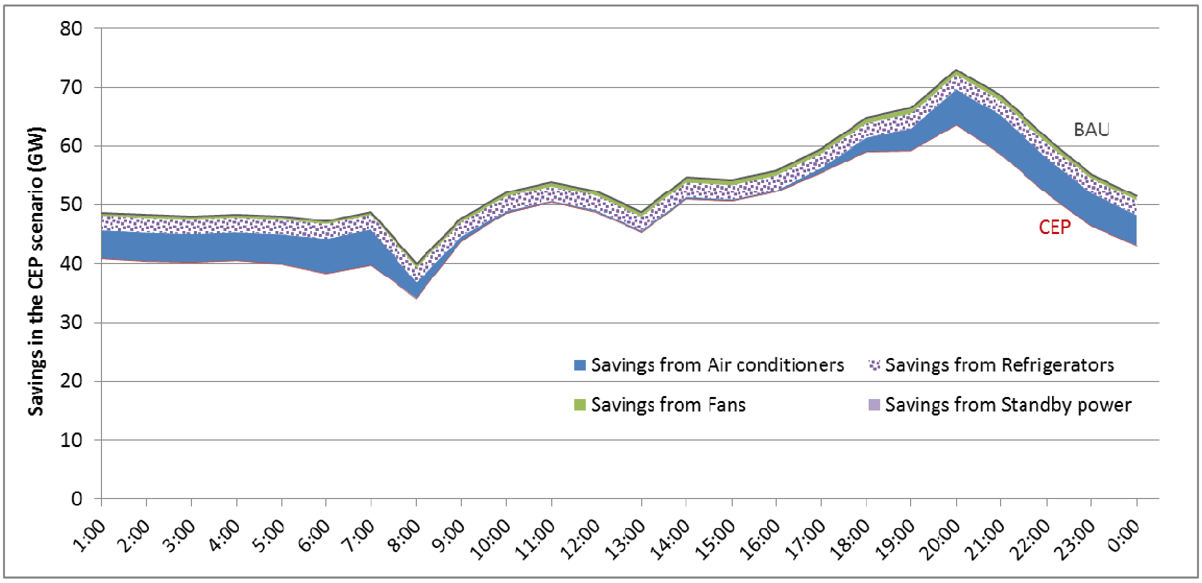


Figure 10 Savings in the CEP scenario in 2030, compared to BAU

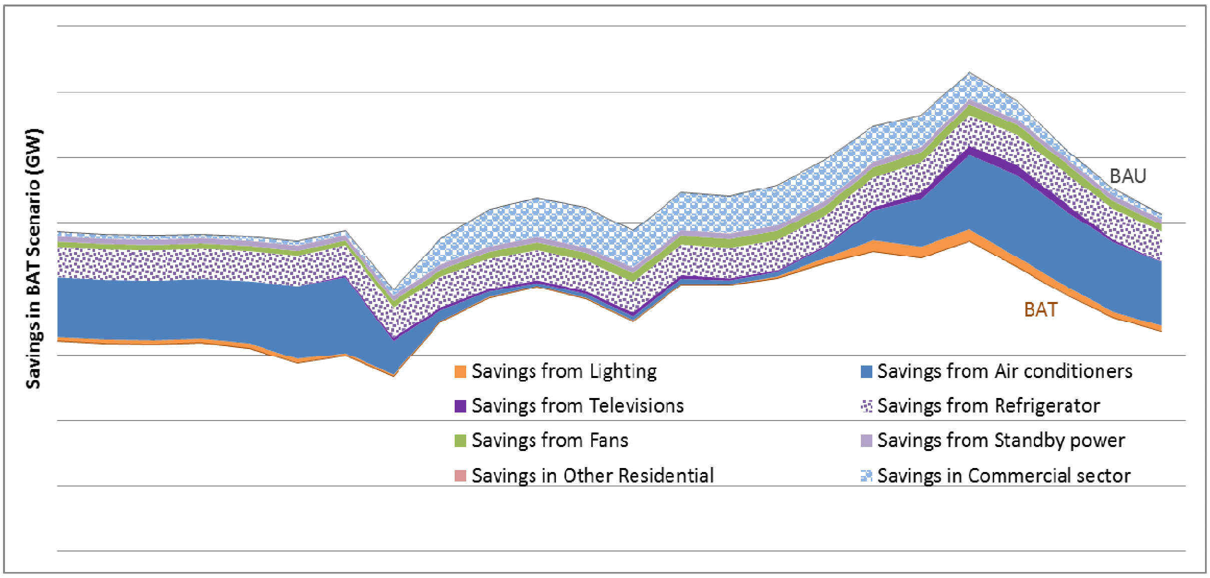


Figure 11 Savings in the BAT scenario in 2030, compared to BAU

Note 1: Savings in Commercial sector is aggregate representation of efficient lighting, air conditioners, and refrigerators in the BAT scenario

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Table 6 Contribution of sectors and end-uses to reduction of peak demand in 2020 and 2030 in the CEP and BAT scenarios

	2020				2030			
	Reduction in CEP		Reduction in BAT		Reduction in CEP		Reduction in BAT	
	(GW)	(%)	(GW)	(%)	(GW)	(%)	(GW)	(%)
Lighting	0.82	1.90%	2.1	4.9%			1.8	2.4%
Refrigerator	0.96	2.22%	1.7	4.1%	2.5	3.4%	4.6	6.3%
Air conditioner	1.10	2.57%	2.1	4.8%	6.1	8.3%	11.3	15.5%
Fans	0.38	0.88%	0.8	1.8%	0.8	1.1%	1.6	2.2%
Televisions			0.7	1.7%			1.5	2.1%
Standby power	0.08	0.19%	0.5	1.1%	0.1	0.2%	0.8	1.1%
Other residential							0.0	0.1%
Commercial sector			1.1	2.6%			4.1	5.6%
Industrial sector								
TOTAL	3.3	7.76%	9.0	20.9%	9.5	13.0%	25.7	35.2%

Conclusion

The analysis presented in this paper demonstrates the potential for extending an energy savings model (BUENAS) to include peak load reduction effects. Results are promising for the case study chosen, which considers likely achievable energy efficiency improvements in the Indonesian appliance and equipment market. First of all, the BAU projection of end use demand concludes that peak electricity load, and therefore generation capacity needs may increase in Indonesia by roughly 3 times over the next 20 years. In order to meet this demand, we estimate that Indonesia will have to build 95 new 500 MWpower plants, confirming concerns about infrastructure constraints, the threat of continued shortages, a massive burden on available capital, and environmental concerns. Alternatively, we find that scenarios that include comprehensive energy efficiency programs could reduce 2030 peak load from 13% to 35% in 2030. With peak load projected to grow by a factor of 3, this corresponds in a reduction in peak load growth of about a fifth to over half.

Importantly, most of these projected savings could come from aggressively targeting just a few residential end uses. For example, air conditioners efficiency alone could save between 6.1-11.3 GW in 2030, corresponding to 12 to 23 500-MW power plants, requiring an investment of several billions of dollars. In other words, potentially billions of dollars of power sector capital could be saved by a targeted program with relatively few actors and stakeholders. While there are likely increased costs to consumers for higher efficiency equipment, in the cost effective potential (CEP) scenario, these capital costs are completely recovered through reduction of consumers energy bills and consumers see a benefit -a past study found that the cost-effective potential in Indonesia could yield to 5 Billion USD savings by 2030 [22]. Programs such as EES&L have a long track record of success in achieving these potential savings and best practices are well known. In fact, the Indonesian government has already embarked on such a set of programs, the effectiveness of which will be largely determined by political will, stakeholder buy in and government technical capacity.

In conclusion, we believe that the results presented here effectively demonstrate a strong incentive for developing countries to aggressively pursue efficiency of domestic appliances for reasons not only of consumer welfare and environmental concerns but also energy security and economic development. Programs to address appliance efficiency in these countries should enjoy a high investment priority therefore, among both developing country governments and the international community that supports their development.

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Heat Pump Tumble Driers: Market Development in Europe and MEPS in Switzerland

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Abstract

Electric laundry driers are becoming increasingly popular in European households. This trend may lead to a significant increase in laundry energy consumption. Heat pump (HP) driers use only 50% of the energy a conventional condensing drier uses. Promoting efficient driers is necessary to limit the expected increase in energy consumption due to electric laundry drying in EU households.

This paper contains an overview of the market in the European Union (EU) for high efficiency driers, as defined by the EU energy label. With over 40% sales share, heat pump tumble driers are clearly succeeding in the European market. Differences between countries are, however, considerable.

Obviously, policies in the EU to promote efficient driers have been effective: the old EU Energy Label created an incentive for new, better technologies and allowed innovative manufacturers to market heat pump driers. The new Energy Label now allows consumers to see the superiority of heat pump over conventional driers with the 'Plus-'classes. Switzerland is even a step ahead: since January 2012, only heat pump driers are allowed on the Swiss market. Also in the USA market, the first heat pump driers have been introduced and policies have begun to adapt to the new drier technologies.

Heat pump tumble driers hold a large energy saving potential in Europe. If all driers sold in Europe were of the A+ class efficiency, it would result in 25% lower energy consumption over the lifetime of the driers sold in a given year. That means some 5.6 TWh of energy or €1.1 billion electricity costs per year could be saved.

Background

About heat pump tumble driers

Tumble driers evaporate the moisture by blowing hot dry air through wet laundry. The air is typically heated by an electric resistance heating element. European driers use one of two different technologies to remove the evaporated water [1]:

1. Vented driers (open systems) blow the moist exhaust air (drawn from the building interior) outdoors, which can cause unwanted smells, steam and noise at the external vent.

2. Condensing driers (closed systems) use a heat exchanger cooled by interior air to condense water from the warm moist air in the drier.

Heat pump driers are usually condensing driers which also integrate a heat pump. Warm, damp air flows out of the laundry drum into the evaporator, where the air is dehumidified and the warm air returned to the drum [2].

Heat pump driers consume only about half of the electricity of conventional condensing driers. This makes them a highly efficient alternative to conventional systems. However, within the group of heat pump driers the energy efficiency varies quite considerably[1]. Due to lower operating temperatures heat pump driers also cause less damage to clothing that other types of driers but increase drying times.

[1] See www.topten.eu

Regulatory context: EU Energy Label and Ecodesign requirements

The original Energy Label for tumble driers was adopted in 1995, and became compulsory in April 1996 [3]. This Label's classification system was based on a simple kWh/kg (consumption per cycle divided by the capacity) efficiency, tested at full load and with 60% initial moisture content (before 2005 the test was performed with 70% initial moisture content). Vented and condensing driers are covered by separate classification schemes. The threshold for condenser drier energy efficiency class A, at 0.48 kWh/kg (with 60% initial moisture content, see [4]), could not be met before the first heat pump tumble driers entered the market in the year 2000 [4]. The new technology with an integrated heat pump however clearly exceeded the A class threshold: first heat pump driers reached efficiency values of around 0.3 kWh/kg from the start, nearly 40% better than the class A threshold.

The aspirational class A of the original Energy Label did a good job of supporting the introduction of this new technology, but once heat pump driers were on the market, class A did not accurately represent the very large efficiency advantage over conventional driers. Conventional driers began to achieve class B only after heat pump driers had entered the market. Also the original Energy Label could not show consumers the significant efficiency differences among heat pump driers, which started to emerge as the technology matured.

The Energy Label was revised in 2012 [5], and addressed these deficiencies by introducing three additional classes, A+ to A+++. This revised Energy Label became compulsory in June 2013 [6], after a transition period. Like under the original Energy Label, classes A and better could only be achieved by heat pump driers (still today, no other technology meets the A class requirements), but since most heat pump driers now achieve A+ class or better performance, the efficiency gap with conventional driers is made visible. Also the 'A Plus'-classes allow consumers to differentiate between more and less efficient heat pump driers. The drawback of the revised Energy Label's classification system is that class A – the class with the most powerful consumer message – is nearly empty, because it defines an efficiency level that heat pump clothes driers have already exceeded.

In addition to different efficiency levels, the revised Energy Label is no longer based on kWh/kg efficiency, but on a more complex Energy Efficiency Index (EEI). The EEI is the relationship of a model's annual energy consumption to the consumption of a reference model of the same capacity (in %). The EEI calculation formula assumes 160 drying cycles per year (around three per week), of which 4 out of seven are assumed to be operated with the drier filled to only half of a full capacity load. The EEI calculation also includes consumption from low power modes (Off and Standby mode). While on the original Energy Label the energy consumption was declared on a per cycle basis, on the revised Label it is declared as annual energy consumption value. Therefore, average energy consumption values according to the original (2004 – 2012) and revised (since 2013) Energy Labels cannot be directly compared.

Table 1: classification of the old and current tumble drier Energy Labels

	Old Label efficiency for condenser driers (in kWh/kg*, until 2012)	**New Label efficiency (EEI, since 2013)**
A+++		EEI < 24
A++		EEI < 32
A+		EEI < 42
A	≤ 0.48 kWh/kg	EEI < 65
B	≤ 0.56 kWh/kg	EEI < 76
C	≤ 0.64 kWh/kg	EEI < 85 (banned from Nov 2015)
D	≤ 0.72 kWh/kg	EEI ≥ 85 (banned since Nov 2013)
E	≤ 0.8 kWh/kg	
F	≤ 0.88 kWh/kg	
G	> 0.88 kWh/kg	

* based on 60% initial moisture content

The revised Energy Label also indicates the duration of the standard drying cycle and, like the original Energy Label, the rated capacity of the drier model and the noise level generated by the standard drying cycle. In the revised Energy Label fiche, manufacturers additionally declare the standard programme's energy consumption at full and half load, the power consumption of low power modes.

For condenser driers, also the condensation efficiency and the condensation efficiency class are indicated.

In the same year as the revised Energy Label, an Ecodesign regulation for tumble driers was adopted and put into force [7]. Tier 1, starting the 1st of November 2013, requires that tumble driers achieve at least energy efficiency class C and condensation efficiency class D, and bans less efficient driers from the market. In November 2015 the requirements will be tightened, and drier models will be required to reach energy efficiency class B and condensation efficiency class C (see table 3).

Tab. 4: Ecodesign requirements for driers

	Min. energy efficiency	Min. condensation efficiency
Tier 1, since Nov. 2013	Class C, EEI < 85	Class D, 60%
Tier 2, from Nov. 2015	Class B, EEI < 76	Class C, 70%

Switzerland: A+ as Minimum Energy Performance Standard

These requirements apply in the entire European Union. Switzerland has been implementing more ambitious Minimum Energy Performance Standards (MEPS). Since January 2012, only class A (according to the original Energy Label) driers may be sold. This regulation effectively banned all non-heat pump tumble driers from the Swiss market. Since January 2015 this requirement has been further tightened to allow only A+ or better, as indicated by the revised Energy Label which Switzerland has also adopted.

Best available technology driers

Brand	V-ZUG	Miele	V-ZUG	Gorenje	V-ZUG	Haier	Samsung
Model	Adora TSL WP	T8877 WP EcoComfort / T 88-79 WP	Adora TS WP	D 7565 NA/NB D 7665N	Adora TL WP	HD70-A82	DV70F5E0HGW/WS
Electricity costs (€ 15 years)	342	356	414	448	450	470	475
Capacity (kg)	7	7	7	7	7	7	7
Drying time (min) full load	130	189	124	155	136	140	150
Energy class	A+++	A+++	A++	A++	A++	A++	A++
Energy (kWh/year)	152	158	184	199	200	209	211
Condensation class	A	A	A	A	A	B	B
Efficency Index	22.9	23.9	27.6	29.6	30	31.7	31
Countries available	CH / on demand	CH / DE / on demand	CH / on demand	on demand	CH / on demand	CH / on demand	CH / on demand

Figure 1: Screenshot from Topten.eu: Most efficient 7-kg-driers

The market information shown in Figure 1 comes from the European Topten website (www.topten.eu) on 15 March, 2015. The best performing driers available have already reached highest available Energy Label classes of A+++ for energy efficiency and A for condensation efficiency. Class A for condensation efficiency means that a maximum 10% of the moisture in the laundry may escape into the room.

5 brands already offer A+++/A models: AEG, Beko, Electrolux, Miele and V-Zug (by 15. March 2015).

Very relevant for consumers is also the duration of the drying cycle. These most efficient models show considerable differences. The V-Zug Adora TS requires only 130 minutes, whereas the Miele T8877 model requires 189 min., nearly one more hour for drying the laundry (source: www.topten.eu).

There are 5 brands of tumble driers for semi-professional use that perform at the A++/A level: Bauknecht, Electrolux, Fors, Schulthess and V-Zug. Semi-professional driers are usually used in multi-family houses (ca. 1 drier for shared use by 5 apartments). The program duration of the quickest machine is just 85 minutes.

Electrolux and Miele also offer professional use heat pump driers with capacities up to 13 kg, corresponding to a 325 liter drum volume. The duration of the drying cycle is only about ¾ hours.

USA: first heat pump driers introduced in 2014

The North American market for clothes dryers is undergoing a transformation towards higher efficiency driven by a combination of improved technology, financial incentives, and product labeling [8]. In 2014, two major appliance manufacturers introduced the first hybrid heat pump electric dryers into the North American market; these new dryers offer a 35% improvement in energy efficiency over the standard electric dryer, with one being vented and the other being unvented. Blomberg has subsequently introduced an condensing heat pump-only model with significantly higher efficiency. In addition, the U.S. federal government's ENERGY STAR program has introduced energy efficiency labeling for dryers in the U.S. for the first time. These developments are due in part to the efforts of utility energy efficiency program providers in the US working together through the Super-Efficient Dryer Initiative (SEDI). SEDI was created in 2008 to accelerate the market introduction of highly efficient dryers into the U.S. and Canada, building off of the successful market introduction of heat pump dryers in Europe [8].

Why is market monitoring important

Energy Labels and MEPS for energy using products are crucial policy instruments that support on-going market transformation towards higher energy efficiency and lower energy consumption. Appropriate levels for Energy Label classes and their relationship with MEPS levels are key for the effectiveness of these policy instruments. If most models on the market are already in the best Energy Label class and no challenging MEPS are implemented, innovation can stall. This can be seen e.g. in past sales data from Switzerland for dishwashers and ovens published in [9]. Label efficiency classes that are still beyond the current market generate market pull, while challenging MEPS levels push poor-performing products to a higher level. Together, these instruments ensure that the efficiency of products continuously improves (e.g. example refrigerators and freezers in [9]).

When defining effective policy measures, it is critical to understand the market in terms of the products being sold and their attributes (including efficiency). Understanding the market empowers policy makers to make orderly and well-informed decisions about the optimal level for new MEPS and Energy Label class limits and the timing of their implementation to achieve maximum effectiveness. If sales data are publicly available over a longer period, it is possible to develop stock models to estimate trends in energy consumption and other attributes [10] – this can be used for assessing past savings from previous policies as well as projecting future savings from proposed new policies (example from Australia on refrigerators: see [11]).

Most economies have a system to monitor the markets for products that are covered by an Energy Label or MEPS, either based on sales data purchased from a professional market research company, or on information on the models that are on the market from mandatory product registration systems [12]. Australia even combines detailed product specifications from the registration database with sales data [13]. Up to today, Europe has neither mandatory product registration nor does it monitor the markets with sales data [9]. Since little is known about actual market trends, it is difficult for policy makers to launch revisions on time and to define Label classes and MEPS at optimal levels.

Data and Methodology

ADEME[2] (Agence de l'Environnement et de la Maîtrise de l'Energie) set up a project together with the Topten team to purchase and analyse sales data on tumble driers for France and Portugal, plus some similar information at the EU level. Data was purchased from GfK, a professional market analysis company active around the world[3]. In Europe, GfK covers around 90% of the tumble driers market, and is present in 24 Member States. Sales data plus many product characteristics are obtained from retailers.

For France and Portugal, GfK provided tumble driers sales data including information regarding energy efficiency classes, average energy consumption and price, and information about capacities, covering the years 2004 to 2014. For an aggregation of 21 EU Member States[4], 2014 data was provided regarding total sales, sales shares of energy classes, and capacities. Sales data of Switzerland was obtained from [9].

All product performance information about specifications was provided according to the declaration on the Energy Label. There was one exception: the declared energy consumption per drying cycle provided under the original Energy Label (until 2012) was multiplied by 160 cycles to obtain an annual energy consumption estimate comparable with the annual energy consumption value that appeared on the revised Energy Label starting in 2012. However, these annual consumption values are not 100% comparable, because the revised Energy Label's value includes part-load drying and consumption from low power modes as described above.

Similar data, including complete information on EU level, was obtained for refrigerators and washing machines, as presented in the EEDAL conference 2015 (papers No. 50 [13] and 147 [14]). A complete report containing the results of sales data analysis for refrigerators, washing machines and tumble driers will be published on www.topten.eu in May 2015 [15].

Results

In France, sales of tumble driers increased by 23% from 2004 to 2014. The climbing sales graph in [15] shows two 'valleys' of lower sales in 2009 and 2013. In 2014, 678'000 tumble driers were sold in France. In Portugal, tumble drier sales varied strongly over the years. After having reached a peak of 63'000 units in 2010, there was a big drop to only 26'000 units in 2012. In 2014, 44'000 tumble driers were sold in Portugal, 26% less than ten years before (2004: 59'000; see [15]). Relative to the population, more than twice as many tumble driers were sold in France than in Portugal in 2014: per 100 inhabitants, 1.04 driers were sold in France, versus 0.42 in Portugal. This is not surprising, since the climate in Portugal allows to dry the laundry by the sun and wind almost throughout the year.

In the EU-21, nearly 3.9 million tumble drier units were sold in 2014. This equals 0.8 units per 100 inhabitants.

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[2] www.ademe.fr/

[3] www.gfk.com

[4] EU-28 without Bulgaria, Luxembourg, Estonia, Latvia, Lithuania, Malta and Cyprus.

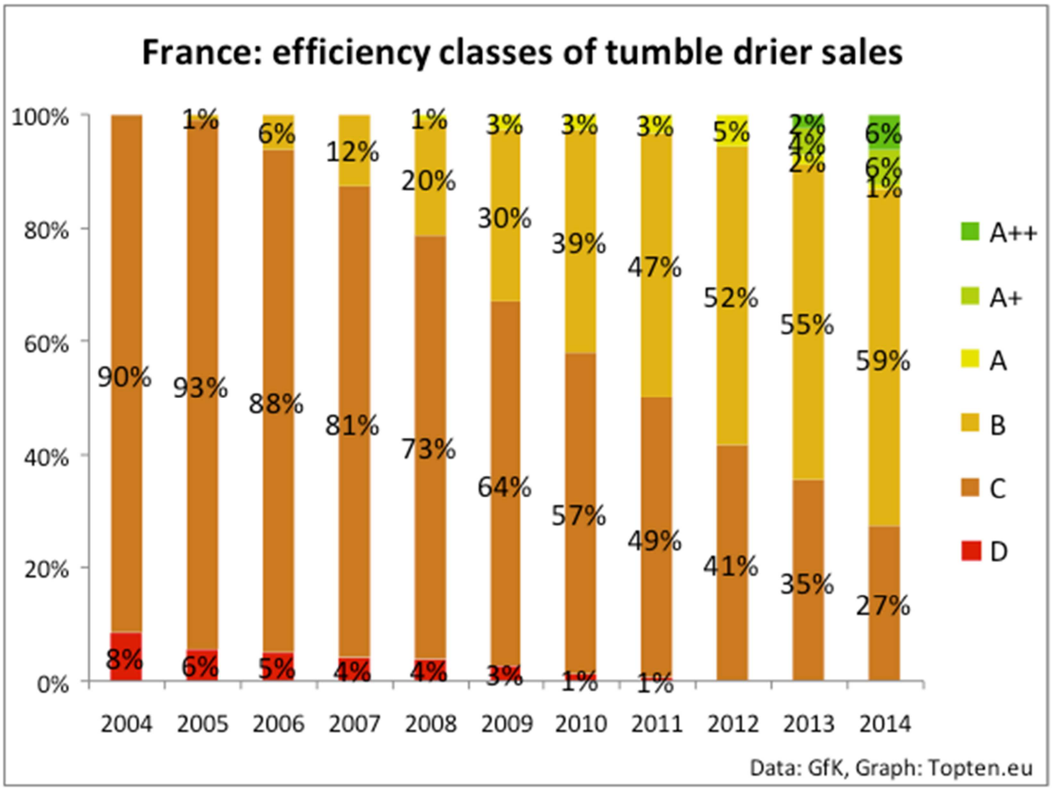

Figure 2: Conventional driers (classes B and C) have been dominating the French drier market

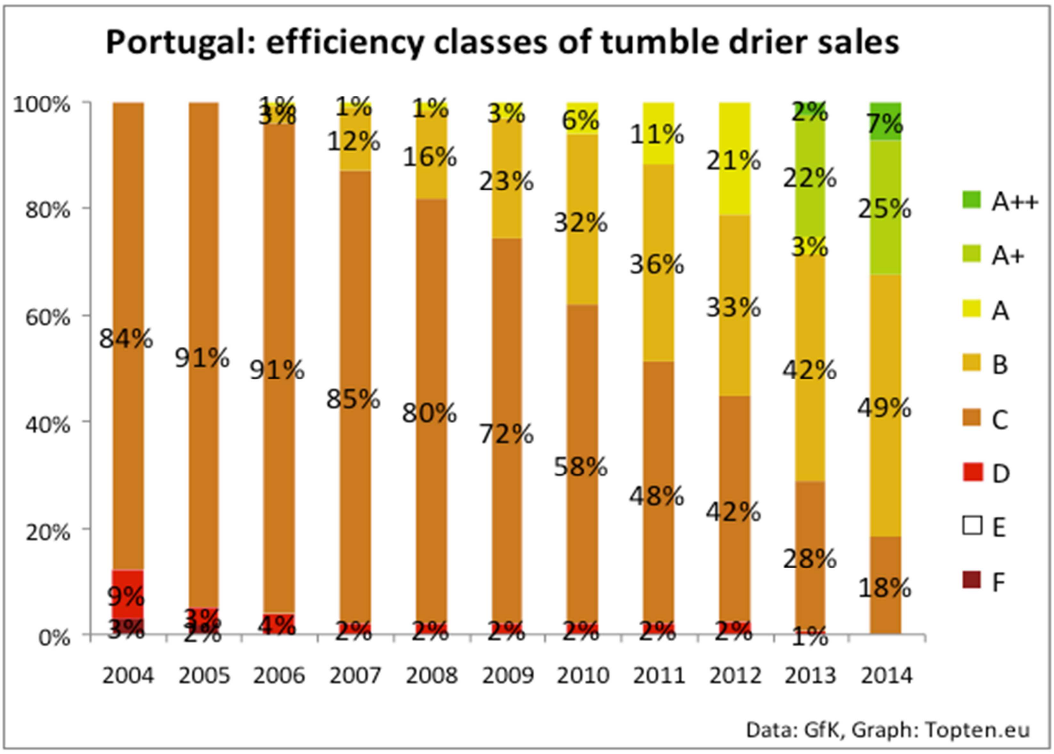

Figure 3: Heat pump driers (classes A/A+ and better) are gaining market share in Portugal

Under the original (pre 2012) Energy Label Class C absolutely dominated the drier markets at the beginning of the ten year period shown in Figure 3. Class B driers started to appear on the French market in 2005, and in Portugal in 2006. While in Portugal heat pump driers (class A) entered the market at the same time as class B conventional driers, class A driers appeared in France starting only in 2008. While the market share of heat pump driers sold has increased steadily in Portugal since 2009, the development went slower in France. Here, the introduction of the revised Energy Label seems to have accelerated the market uptake.

In 2014, heat pump driers (classes A and better) accounted for only 13% of all drier sales in France, but for 32% in Portugal. Both the French and Portuguese drier markets lag behind the EU average. The differences are large among countries, as is underlined by Fig. 4: across the EU, in 2014 heat pump driers accounted for a staggering 43% of total drier sales! According to information from GfK it is not the big countries that drive the high efficiency of the EU drier market, but rather a high number of not so large markets that show a preference for high efficiency driers – especially in Southeastern Europe. In these markets, electric driers are not very common; but if people do buy one, it is usually an energy efficient model.

The tier 1 MEPS, banning class D starting November 2013, seems to have had very little impact – at least in the two countries considered in this paper. The tier 2 MEPS will certainly have some effect, leaving only conventional class B driers on the market. It is not surprising that with the introduction of the revised Energy Label in 2013 class A virtually disappeared (since it is located at the 'technology gap', see above). The fear that the strong communicative value of class A might create an incentive for less efficient heat pump driers seems not to be justified. Instead the revised Energy Label offers the possibility to market even more efficient heat pump driers as such, and allows consumers to tell less and more efficient heat pump driers from each other. The positive effect can clearly be seen on EU level!

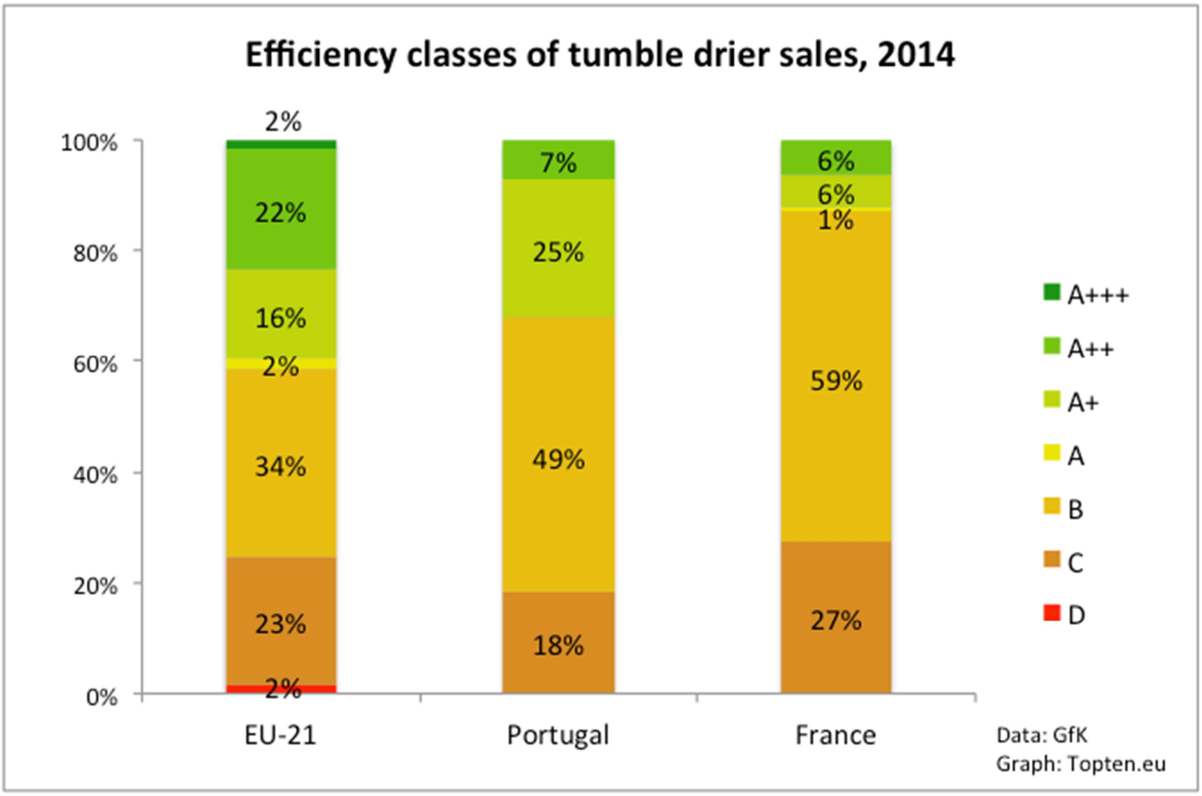

Figure 4: In 2014, heat pump driers accounted for 42% of the total sales across the EU

Sales data from Switzerland, published annually [9], shows a very different picture: by 2011 class A driers already accounted for close to a 50% market share, then the stringent MEPS drove it to 100% in 2012. In Switzerland the revised Energy Label was introduced later than in the EU, therefore the new classes appear only in 2014 and also 2013 sales show a 100% market share for A class.

Note to the reviewers: for the presentation in August 2015, 2014 sales data from Switzerland will be available, also showing A+, A++ and A+++ sales according to the revised Energy Label.

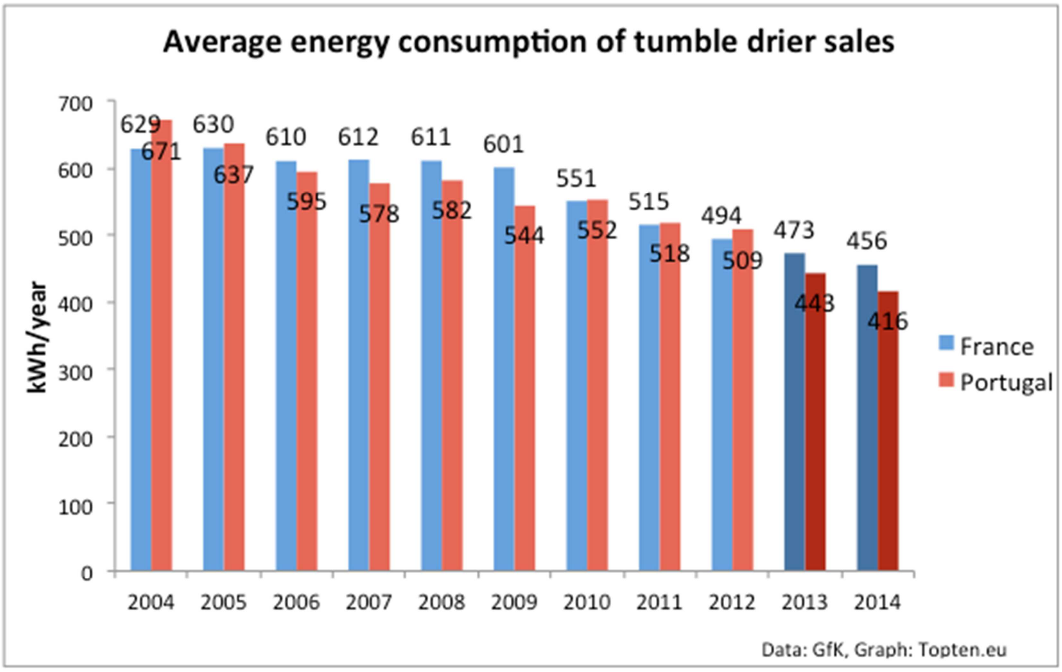

Figure 5: Average declared energy consumption clearly went down in both countries

Note: Declared energy consumption according to the old Label (2004 – 2012, in kWh/cycle) has been multiplied by 160. It is however not completely comparable with the declaration on the new Label, because this includes part load drying and low power modes consumption.

The average declared energy consumption of tumble driers sold in Europe decreased both in France (by 28%) and Portugal (38%) between 2004 and 2014. It has to be kept in mind that energy consumption values before and since 2013 cannot be directly compared. While for Portugal indeed a 'jump' to lower average energy consumption from 2012 to 2013 in visible in Fig. 5, no change can be seen in the French sales data.

While the average energy consumption was yet higher in Portugal than in France in 2004 (probably due to class F driers being on the market, see Fig. 3), in 2014 the average consumption of Portuguese driers was 9% lower than that driers being sold in France.

Obviously the declared energy consumption is more strongly influenced by energy efficiency than drier size (capacity; Figs 6 and 7): in France the average declared energy consumption went clearly down in the ten year period, while at the same time there was a strong trend to larger capacities. And Portuguese driers consumed lower energy than French driers in 2014, even though Portuguese seem to prefer larger driers. This is in contrast to washing machines, where Portuguese sales consume more energy than the EU and French average, despite being of higher efficiency – because also here the machines sold in Portugal are of larger size [14].

Ten years ago, both in France and Portugal driers were usually designed for 6kg or less laundry. In 2014, most driers sold in Portugal can dry 8 kg (+ 30%), and between 7 and 8 kg in France. This trend to larger models seems to be even faster than for washing machines, where a similar development is shown in [total report]. As in the case of washing machines it is questionable if this trend is really originating from changed consumer demand, especially since the average household size is becoming smaller. Instead, the development could mainly be steered by the market offer. It is possible that thanks to the development of smaller components the drum can be larger even within an equally-sized housing.

Unlike it is true for washing machines [14], modern more energy efficient tumble driers are not larger than less efficient models, as shown in Fig. 10 below. The new EEI system includes half load drying efficiency, so drier models must also dry efficiently if only loaded partly. And the reference energy consumption (SAEc) does not increase strictly linearly with capacity but includes capacity to the power of 0.8 ($c^{0.8}$). Also there is no obvious link to pricing policies: in Portugal prices are increasing with average capacity (Fig. 8), but in France prices are stable despite more larger driers being sold.

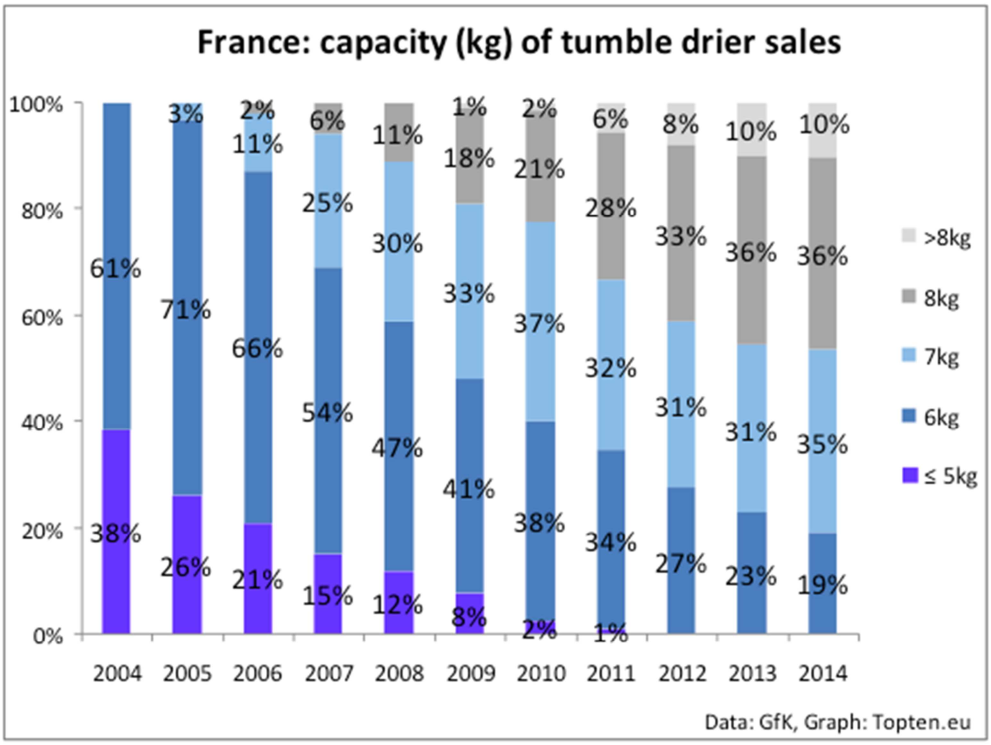

Figure 6: There is a clear trend to larger tumble driers in France

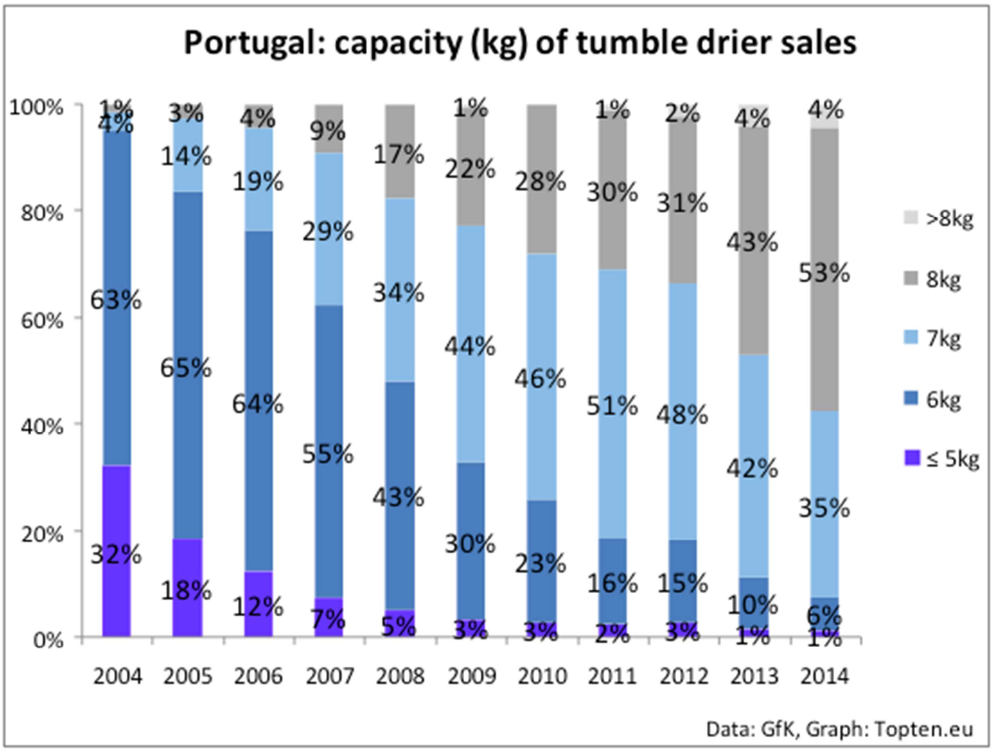

Figure 7: Also in Portugal driers are getting larger

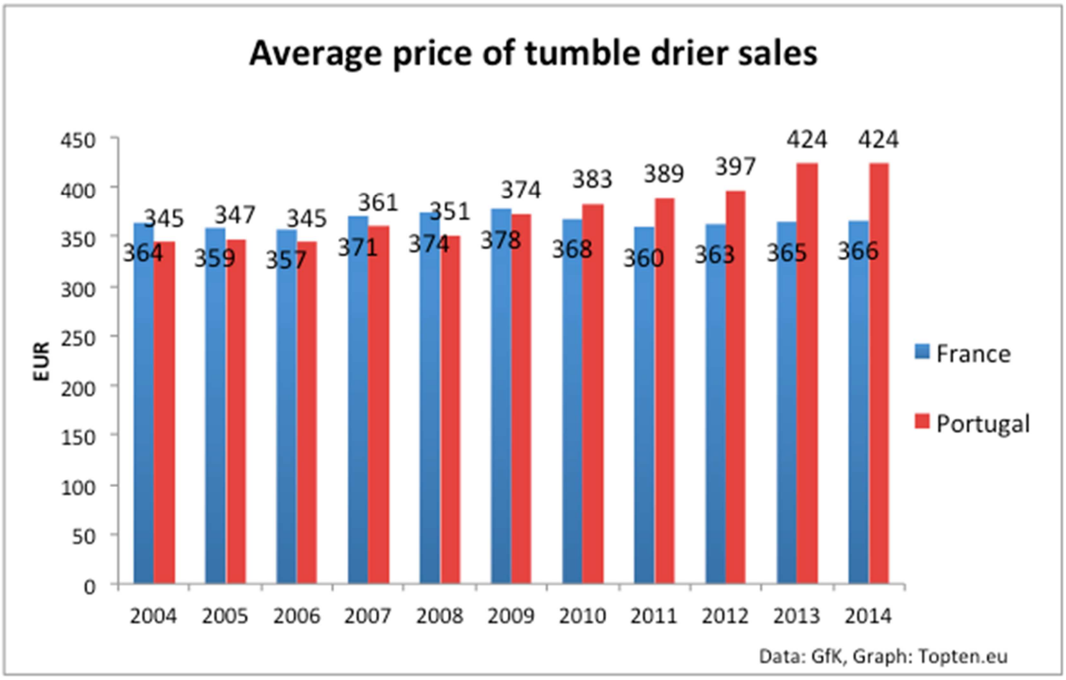

Figure 8: Different price developments in France and Portugal

Tumble driers price in France has been relatively stable over the last decade – despite larger appliances. In Portugal we observe a slight but steady price increase of 23% (average of 1,6% per year) over the 10-year period between 2004 and 2014. The price development might partly reflect the size increase of around 30%. And since 2013 the new Label with A+ and A++ driers seems to have brought higher prices in Portugal.

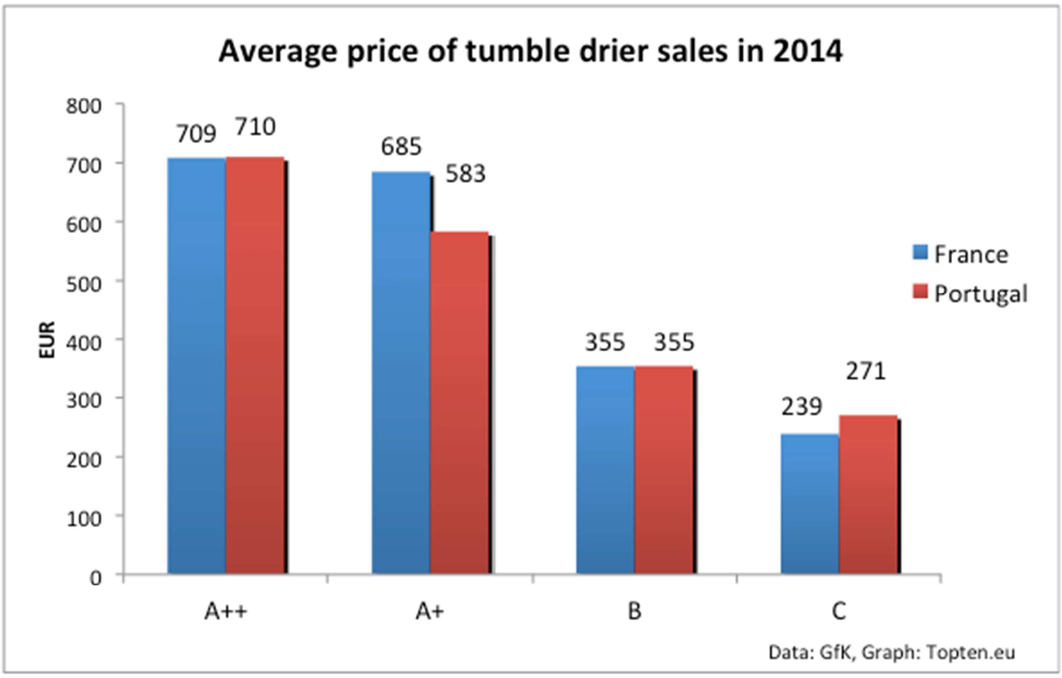

Figure 9: Not surprisingly, more efficient driers have higher average (nominal) prices

Note: class A is not included in this graph, because A class driers are nearly non-existent

Both for France and Portugal, we observe higher prices associated to driers with higher energy effciency class. In 2014, average nominal prices for efficiency classes were nearly the same in France and Portugal – except for class A+. For driers of the efficiency class, French consumers paid more than EUR 100 more than Portuguese. The price difference of these heat pump driers is reflected in different sales shares in the two countries: while in Portugal A+ driers accounted for 25% of the total sales in 2014, in France they mad up only 6% (Figs 2 and 3). For A++ driers on the other hand, where the prices are nearly identical, also the sales shares are nearly the same: 7% in Portugal and 6% in France. The low sales share of A+ driers in France is certainly linked to high average prices.

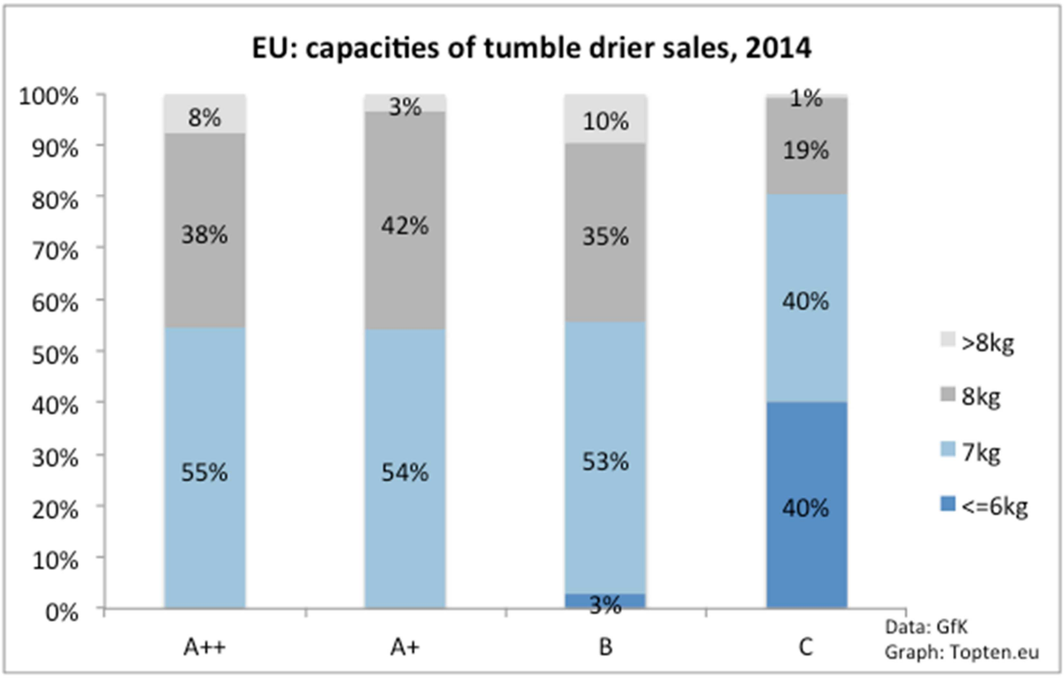

Figure 10:There is no correlation between capacities and energy efficiency class

Note: class A is not included in this graph, because A class driers are nearly non-existent

For washing machines, there is a clear correlation between capacity and energy efficiency class [14]: more efficient washing machines are on average larger. This is not true for driers as Fig. 10 shows. Class C driers, to be banned from the EU market from November 2015, are smaller than more efficient driers. Models with 6kg capacity and less are literally non-existent in driers of classes B and better. Instead, 7-kg-models account for the majority of sales in all other classes with considerable market share B, A+ and A++.

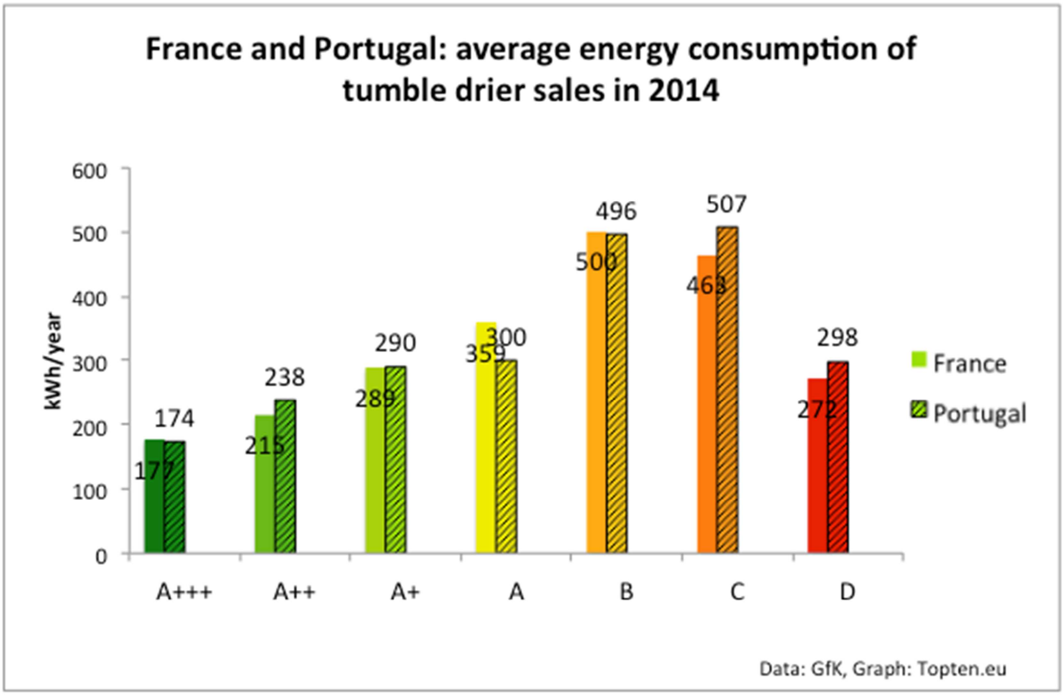

Figure 11: Heat pump driers hold a big saving potential

Figure 11 finally shows that the important energy saving potential lies in the promotion of heat pump tumble driers, without compromises. Fig. 11 even questions the energy saving impact of tier 2, which will ban class C driers from the market starting from November 2015: surprisingly, average energy consumption of the 2014 sales is not lower for class B driers than class C (in detail: it is 2% lower for Portugal, but 8% higher for France)! This effect is likely a combination of an increase in size from class C to B (Fig. 10) and low improvement in energy efficiency: class C is only a 11% 'wide', while other classes require up to 25% (A++, A+++) and even 35% (A+) efficiency improvement.

A jump from class B to A+, from conventional to 'basic' heat pump driers, means an average energy reduction of over 200 kWh/year (-42%) in both countries. More than an average of 300 kWh/year or 65% can be saved per appliance with a jump to A+++.

Conclusions and energy saving potential

With over 40% sales share, heat pump tumble driers have clearly reached the breakthrough on the European market. Differences between countries are however considerable, and it seems that they are linked to factors such as price and legislation: the low share of A+ driers in France compared to the EU average and Portugal might be linked to high average prices. And in Switzerland heat pump driers hold 100% market share – clearly supported by the stringent MEPS that have been introduced in 2012.

Policies in the EU also have been effective: the original Energy Label created an incentive for new, better technologies and allowed innovative manufacturers to market heat pump driers as high efficiency models. The revised Energy Label now allows consumers to see the superiority of heat pump over conventional driers with the 'Plus-'classes. While tier 1 of the Ecodesign regulation was of little effect, the impact of tier 2, banning class C, is questionable due to small efficiency improvements to class B, which may even be outweighed by larger size.

Still these policy measures certainly supported the reduction of the average energy consumption of driers by between around 30% and 40% in the past ten years. The real, big saving potential however lies in heat pump driers, as shown in Fig. 11 and Fig. 12 below.

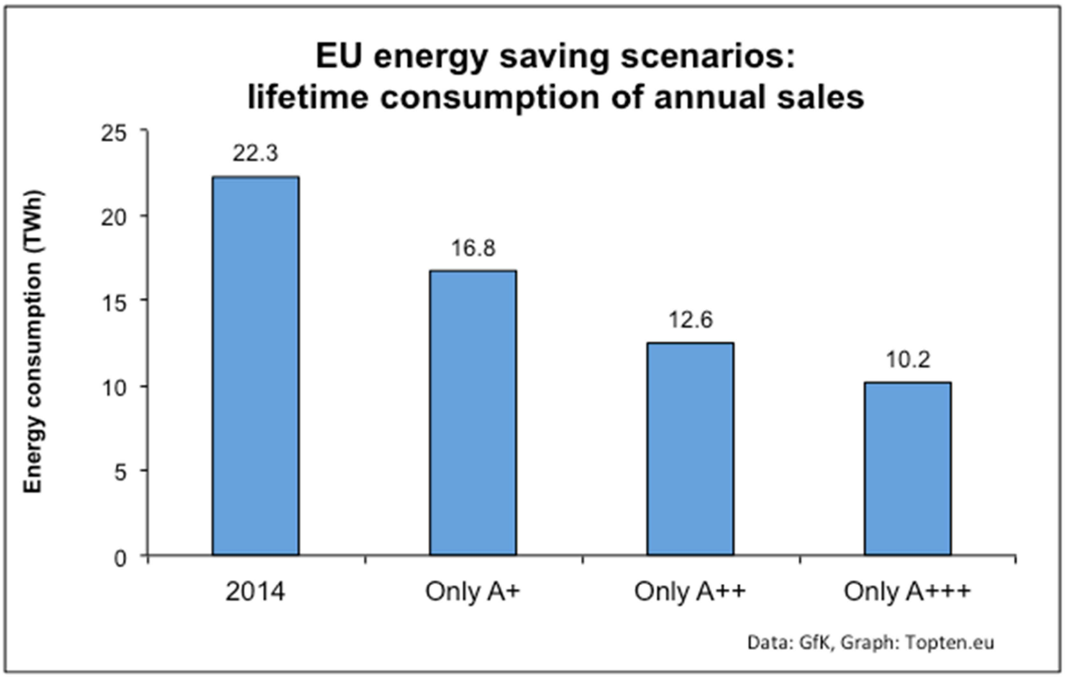

Figure 12: Heat pump tumble driers hold a large energy saving potential in Europe

The total energy consumption of all driers purchased in Europe in 2014 was calculated, assuming a lifetime of 15 years. Several hypothetical scenarios were studied, in order to evaluate the potential energy savings available from sales of more energy-efficient driers.

- Scenario 1: all driers sold in Europe are A+ class. This scenario would result in 25% lower energy consumption over the lifetime of the driers sold in a given year. That means some 5,6 TWh of energy saved, the equivalent annual output of 1.4 medium-sized coal power plants. In economic terms, Europe would save €1.1 billion per year.[5]
- Scenario 2: all driers sold in Europe are A++ class. This scenario would result in 44% lower energy consumption over the lifetime of the driers sold in a given year. That means some 9,8 TWh of energy saved, the equivalent annual output of 2.4 medium-sized coal power plants. In economic terms, Europe would save €2 billion per year.
- Scenario 3: all driers sold in Europe are A+++ class. This scenario would result in 54% lower energy consumption over the lifetime of the driers sold in a given year. That means some 12,1 TWh of energy saved, the equivalent annual output of 3 medium-sized coal power plants. In economic terms, Europe would save €2.4 billion per year.

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Study of Chinese New EES for Variable-Speed Air-conditioners, Washing Machines and Panel-TVs

ZHAO Feiyan, Huang Luting, HU Bo, ZHENG Tan

Top10 China

Abstract:

In 2012, China's National Development and Reform Commission (NDRC) and Standardization Administration of China (SAC) jointly launched the "One hundred Energy Efficiency Standards Program" to develop or revise 100 energy efficiency standards (EES) and Quota (energy consumption per unit output) standards in 2 years. For household appliances, the EES of variable-speed (VS) air-conditioners, washing machines and panel-TVs have been revised in 2013. Compared with the old standards, the new standards improved the requirements for each energy efficiency grades and defined new energy efficiency parameters and test methods. Following the EES revision, some mandatory energy labels were also revised.

In this paper, the new Chinese EES for VS air-conditioners, panel-TVs and washing machines are introduced in details. An investigation based on China's retail market data and government data has been done, and it analyzes the market changes of each energy efficiency grades for every kind of appliances after one year implementation of the new standards. This paper also provides suggestions improving current EES of household appliances.

1. Washing machines

1.1 Product background

China started producing washing machines from 1970s, now has become the biggest washing machine producer and user in the world. With the wide deployment of washing machines in 1990s and 2000s, the productivity and sales of washing machines in China began to reduce in recent years. It is reported China produced about 35.7 million washing machines in 2011, reduced about 42.5% compared with 2010. The domestic sale of washing machines is 34.4 million in 2012, reduced about 3.8% compared with 2011[1]. The Chinese ownership of washing machine was about 350 millions in 2012, China is still one of the biggest producer and consumer of washing machines in the world[2].

There are two main kinds of washing machines: drum washing machines and impeller washing machines. Double cylinder washing machines were popular in 1980s and 1990s, but have very small market share now. According to the market research of Top10 China in 2014, 49% washing machines in Chinese market are drum washing machines, 48% products are impeller washing machines and the double cylinder washing machines only have 3% market share[3].

1.2 EES changes of washing machines

The first EES of washing machines was released in China in 2004 named <GB 12021.4-2004 The maximum allowable values of the energy consumption and energy efficiency grade for household electric washing machines>, then the China energy label of washing machine was implemented in 2007, which was based on GB12021-2004[4]. From October 2013, the new MEPS for washing machines <GB12021.4-2013 Maximum allowable values of energy, water consumption and grades for household electric washing machines> began to be implemented. Compared with GB12021.4-2004, GB12021.4-2013 improves the energy efficiency requirements significantly, defines the water efficiency grades and redefines the methods to calculate the energy and water consumption[5].

(1) Energy efficiency requirements improved

There are 5 energy efficiency grades classified in washing machine EES, and covered 3 different kinds of washing machines: drum washing machines, impeller washing machines and double cylinder washing machines. Impeller washing machines and double cylinder washing machines share the same requirements. The following table 1 and 2 show the energy efficiency requirements change between GB12021-2004 and GB12021-2013.

For impeller washing machines, the new EES eliminates grade 4 and grade 5 products from the market. The former grade 3 requirements become the minimum energy performance indicator in the new EES.

Table 1 Energy efficiency requirements changes of impeller washing machines and double cylinder washing machines

Grade	Energy consumption (kWh)/(cycle.kg)		Water consumption L/(cycle.kg)		Rate of washing ability	
	GB12021-2004	GB12021-2013	GB12021-2004	GB12021-2013	GB12021-2004	GB12021-2013
1	≤0.012	≤0.011	≤20	≤14	≥0.90	≥0.90
2	≤0.017	≤0.012	≤24	≤16	≥0.80	≥0.80
3	≤0.022	≤0.015	≤28	≤20	≥0.80	≥0.80
4	≤0.027	≤0.017	≤32	≤24	≥0.70	≥0.80
5	≤0.032	≤0.022	≤36	≤28	≥0.70	≥0.80

For drum washing machines, grade 2,3,4 and 5 products are all kicked out from the market. The old grade 1 requirements become the minimum energy performance indicator in the new EES.

Table 2 Energy efficiency requirement changes of drum washing machine

Grade	Energy consumption (kWh)/(cycle.kg)		Water consumption L/(cycle.kg)		Rate of washing ability	
	GB12021-2004	GB12021-2013	GB12021-2004	GB12021-2013	GB12021-2004	GB12021-2013
1	≤0.190	≤0.110	≤12	≤7	≥1.03	≥1.03
2	≤0.230	≤0.130	≤14	≤8	≥0.94	≥1.03
3	≤0.270	≤0.150	≤16	≤9	≥0.94	≥1.03
4	≤0.310	≤0.170	≤18	≤10	≥0.70	≥1.03
5	≤0.350	≤0.190	≤20	≤12	≥0.70	≥1.03

(2) Water efficiency grades defined

Besides the huge upgrade of energy efficiency requirements, GB12021-2013 also defines water efficiency grades on the base of EES. It means the product can be classified on the water consumption efficiency requirements only when it can meet the MEPS. Following table 3 and table 4 show the water consumption efficiency requirements defined in GB12021-2013.

Table 3 Water consumption efficiency requirements of impeller washing machines and double cylinder washing machines

Grade	Water consumption L/(cycle.kg)
1	≤10
2	≤14
3	≤18
4	≤22
5	≤28

Table4 Water consumption efficiency requirements of drum washing machine

Grade	Water consumption L/(cycle.kg)
1	≤6
2	≤7
3	≤8
4	≤10
5	≤12

Although the EES for washing machines has already defined the water efficiency grades, the China energy label for washing machines didn’t include such information yet. Normally drum washing machines consume more energy than impeller washing machines, but consume less water than impeller washing machines in China. For consumers, it is very helpful to know both the energy efficiency grades and water efficiency grades of the washing machine to make a wiser decision.

(3) Methods to calculate the energy and water consumption redefined.

According to the household appliances using habit investigation finished by CLASP in 2014, in China washing machines seldom work with rated washing load, mostly with half or 2/3 load[6]. GB12021-2013 redefines the method to test and calculate the energy and water consumption, considering rated load and half load both, which is closer to the real washing situation.

The formula to calculate energy consumption：

$E_e=I_e*(E_1+2E_2)/(2m)$

E_e: energy consumption per kilogram. (kW•h)/(cycle•kg)

I_e：energy efficiency compensation coefficient, for impeller washing machine it is 0.75, for drum washing machine it is 0.85.

E_1：energy consumption of washing cycle with the rated washing capacity. kW•h

E_2：energy consumption of washing cycle with half-rated washing capacity. kW•h

m：rated washing capacity. kg

The formula to calculate the water consumption：

$W_e=I_w*(W_1+2W_2)/(2m)$

W_e: water consumption per kilogram. L/(cycle•kg)

I_w：water consumption efficiency compensation coefficient. 0.75

W_1：water consumption of washing cycle with the rated washing capacity. L

W_2：water consumption of washing cycle with half-rated washing capacity. L

m：rated washing capacity.kg

As showed in the first formula, the energy efficiency compensation coefficient is different for impeller washing machines and drum washing machines, the result of energy consumption for drum washing machines will be bigger than impeller washing machines even though the test results are the same.

1.3 Grades distribution

Based on washing machines information collected from China market and government data, the distribution of energy efficiency grades was analyzed. Before the revision of GB12021.4-2004, grade 1 washing machines took 28% market share, which reduced to about 14.5% after the revision. Grade 2 washing machines' market share increase from 36.2% to 38.5%, which means more than half washing machines in the market can be certified as energy saving products (EES sets grade 2 requirements as the minimum requirements for energy-saving products certification).

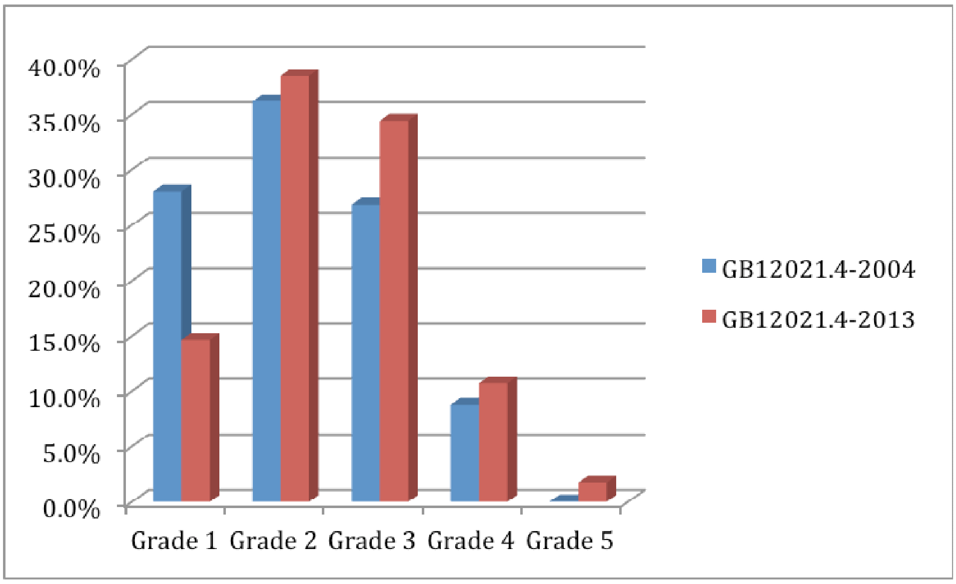

Figure 1 Grades distribution change of washing machine

2 VS air-conditioners

2.1 Product background

VS air conditioners were introduced into Chinese market in the 1990s. Sales remained low until 2009. In 2010 and 2011, sales doubled on an annual basis, with the VS air conditioner market share growing from 16% in 2009 to 35% in 2011. From 2012, the productivity and sales of VS air-conditioners both reduced. It is reported the domestic sales of VS air-conditioners was 24 million in 2012 and the ownership was above 40 million in 2012[7].

2.2 EES changes of VS air-conditioners

The first EES for VS air-conditioners was published in 2008 named <GB 21455-2008 Minimum allowable values of the energy efficiency and energy efficiency grades for variable speed room air conditioners>, the energy labeling of VS air-conditioners started in 2009 based on GB 21455-2008[8].

The new version of GB21455-2008 has been released in 2013 and been implemented since October 1st 2013. Compared with GB21455-2008, GB21455-2013 defines the annual performance factor (APF), enhances the energy efficiency requirements and reduces the energy efficiency grades[9].

(1) APF defined

APF is the ratio of heat insufflated in and taken from the room to the electricity consumed by the VS air conditioner for one year, which is the parameter to measure the energy efficiency of the VS air-conditioners with heating pump, while seasonal energy efficiency ratio (SEER) is the parameter to measure the energy efficiency performance of VS air-conditioners without heating function. GB21455-2013 regulates the testing annual heating time is 433 hours and cooling time is 1136 hours. Following table 5 shows the APF requirements in GB21455-2013 classified on the cooling capacity.

Table 5 APF requirements for heat pump VS air-conditioners

Rated cooling capacity	APF Wh/Wh		
	Grade 1	Grade 2	Grade 3
<=4500W	4.5	4.0	3.5
4500W-7100W	4.0	3.5	3.3
7100W-14000W	3.7	3.3	3.1

(2) Energy efficiency requirements improved

GB21455-2013 eliminated former grade 4 and grade 5 VS air-conditioners out from the market and improved the SEER requirements of grade 1,2 and 3, as showed in table 6.

Table 6 SEER requirements changes

Rated cooling capacity	SEER Wh/Wh							
	Energy efficiency grade							
	1		2		3		4	5
	GB 21455-2008	GB 21455-2013	GB 21455-2008	GB 21455-2013	GB 21455-2008	GB 21455-2013	GB 21455-2008	GB 21455-2008
<=4500W	5.2	5.4	4.5	5.0	3.9	4.3	3.4	3.0
4500W-7100W	4.7	5.1	4.1	4.4	3.6	3.9	3.2	2.9
7100W-14000W	4.2	4.7	3.7	4.0	3.3	3.5	3.0	2.8

Following the changes of EES, energy label of VS air-conditioner was also revised. Besides the rated cooling capacity and cooling season energy consumption, the new label adds APF, rated heating capacity and heating season energy consumption information on the label. Figure 2 is the new label sample of VS air-conditioner.

Figure 2 New energy label of VS air-conditioner based on GB21455-2013

2.3 Grades distributions

After one-year implementation of the new EES, grade 1 market share of VS air-conditioners decreased from 19% to 10%, grade 2 market share decreased from 46% to 44.5%, while grade 3 market share increased from 29.6% to 49.6%.

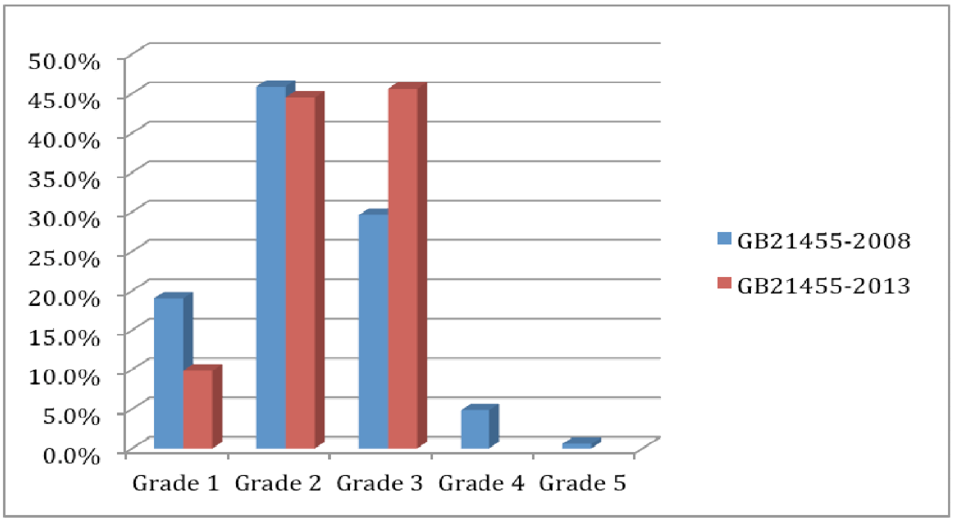

Figure 3 Grades distribution of VS air-conditioners

3 Panel-TVs

3.1 Product background

After 60 years development when the TV was firstly produced in China, it has become one of the household appliances with the highest market penetration. The ‘per hundred households’ penetration rate of panel-TVs in rural areas was about 116.9 units in 2012, while in urban areas the rate was 118.3 in 2012. Since 2012, the demand from rural areas is bigger than the demand from urban areas, with a rate of about 51:49. It is estimated that rural areas will become even more important markets for TV sales in the next few years in China.

There are two types of flat panel technologies: PDP (plasma display panels) and LCD (liquid crystal displays). Although PDP TVs can still be found on the market, they take only a very small market share of 2%. LCD TVs have become the absolute mainstream technology. LCD TVs are illuminated either by LEDs (light emitting diodes) or CCFL (cold cathode fluorescent lamps), depending on the different backlight technologies. EES of panel-TV defined the energy efficiency requirements separately for LCD TVs and PDP TVs.

3.2 EES changes and label of TV

Chinese government released the first EES for flat panel TVs (GB24850-2010) in 2010. GB 24850-2010 not only regulated the energy efficiency requirements, but also the test method. Energy efficiency index (EEI) is defined to measure the energy efficiency performance of TVs, which is the ratio of the energy efficiency of the tested TVs to reference energy efficiency value provided by EES[10].

GB24850-2010 was revised in 2013 and has been implemented since October 1st 2013. Compared with GB24850-2010, GB24850-2013 improves the energy efficiency requirement significantly, defines the on mode static power, on mode dynamic power and the fluctuation values of power, revises the value of the signal processing power[11].

(1) Energy efficiency requirements improved significantly

Panel-TVs are classified into 3 grades based on the value of EEI. For LCD panel-TVs, the minimum energy performance indicator of GB 24850-2013 is even higher than grade 2 requirements of GB 24850-2010. For PDP panel-TVs the grade 1 requirements of GB24850-2010 become the minimum energy performance indicator of GB 24850-2013, which means the grade 3 LCD panel-TVs, grade 2 and grade 3 PDP panel-TVs would be eliminated from the market. Table 7 gives out the details of EEI requirements changes.

Table 7 EEI changes of GB24850-2013

Grade	Energy efficiency ratio of LCD panel-TVs		Energy efficiency ratio of PDP panel-TVs	
	GB24850-2010	GB24850-2013	GB24850-2010	GB24850-2013
1	1.4	2.7	1.2	2.0
2	1.0	2.0	1.0	1.6
3	0.6	1.3	0.6	1.2

(2) Method to define on mode power changed

The on mode power of panel-TV is determined by on mode static power and on mode dynamic power in the new standard. So the TVs need to be tested by both static signals and dynamic signal. In the old standard, only the power using dynamic signals needs to be tested.

(3) Signal processing power value changes

The Formula to calculate energy efficiency of panel-TVs:

$$Eff=(L*S)/(P_k-P_s)$$

Eff：energy efficiency of panel-TV

L：brightness of the TV

S：screen size

P_k：on mode power

P_s：signal processing power

The Ps has been decreased 6-7 W in the new standard, which can result in the increase of Eff compared with the old standard, also can increase the value of EEI.

3.3 Grade distributions

Because of the implementation of new EES, the percentage of grade 1 panel-TVs reduced from 73.8% to 13.6%. The percentage of grade 2 increased from 18.8% to 56.1%. Grade 3 percentage increased from 7.4% to 30.3%.

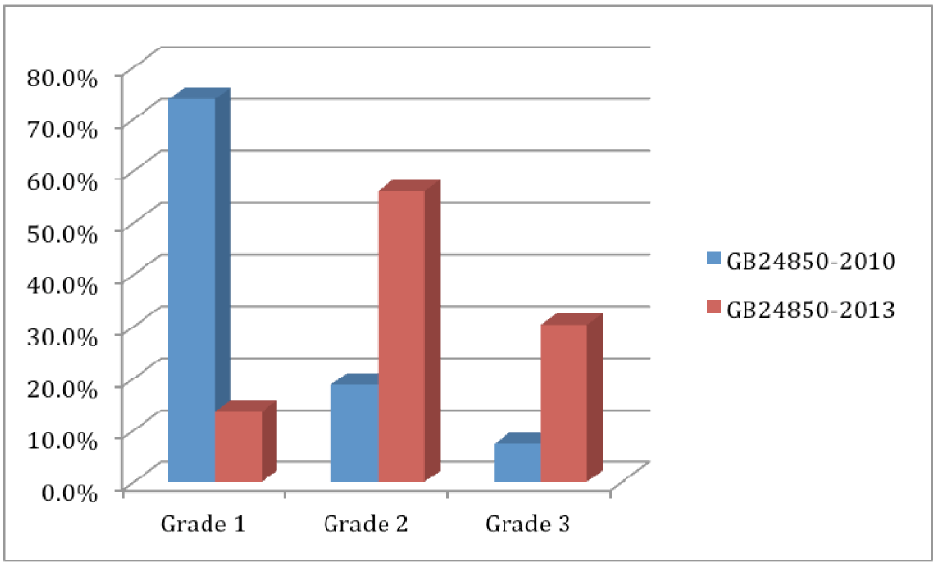

Figure 4 Grades distribution changes of panel-TVs

4 Conclusions and Recommendations

EES and energy label play very important role in improving the energy efficiency of household appliances, eliminating inefficient products, promoting the technology development and guiding the consumption. But with the rapid development of technology, the EES and energy label implementing rules are easily to be out of date which may confuse the market or block the technology development. As mentioned above, washing machine's EES was revised after 9 years, which is too old to promote the development, the technology changed, the using habit changed and the market changed. There should be a timeline of the EES revision set by government. The market monitor mechanism is also need to be established. Grade 1 panel-TV's percentage was already more than 70% just after 3 years of the first panel-TV EES published, which means the requirement of grade 1 is too low, most products can meet the requirement and there should be a further revision. The market monitor mechanism can help reflect the real market change in time and provide evidences for the standard revision.

As mentioned in Market Analysis of China Energy Efficient Products (MACEEP): the standard revision should keep the principle of technology neutrality, which include the different base value for LCD panel-TVs and PDP panel-TVs when calculating the energy efficiency index, and the difference value of energy efficiency compensation coefficient for impeller washing machine and drum washing machine.

Following the changes of EES, the energy label should also be revised to provide the important and necessary information to consumers: the water efficiency grades are important information for consumers when purchasing which should be added to the energy label of washing machines. The power of panel-TV is the direct information of energy consumption which also should be added to the energy label of panel-TVs.

Reference or reasons need to be provided to explain some given values in EES, such as: the energy efficiency compensation coefficient and water compensation coefficient of washing machines. The energy efficiency compensation coefficient of impeller washing machines is 0.75, which is 0.85 for drum washing machines. The water compensation coefficient is 0.75. It was recommended that more transparency or explanatory documents are needed in such circumstances.

Reference

[1] CNIS (2012): China National Institute of standardization: White paper for the energy efficiency status of China energy-use products.

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[3] HU Bo, ZHENG Tan, Jayond Li, Steven Zeng. (2013): Market Analysis of China Energy Efficient Products.

[4] GB12021.4-2004 < Maximum allowable values of the energy, water consumption and grades for household electric washing machines>.

[5] GB12021.4-2013 <Maximum allowable values of the energy, water consumption and grades for household electric washing machine>.

[6] CLASP(2014): Investigation report on consumers' recognition of energy labels and household appliances using habit.

[7] National bureau of statistics of China (2013): Annual report of the income of urban and rural residents.

[8] <GB 21455-2008 Minimum allowable values of the energy efficiency and energy efficiency grades for variable speed room air conditioners>.

[9] <GB 21455-2013 Minimum allowable values of the energy efficiency and energy efficiency grades for variable speed room air conditioners>.

[10] GB24850-2010 <The maximum allowable values of the energy efficiency and energy efficiency grade for flat panel televisions>

[11] GB24850-2013 <The maximum allowable values of the energy efficiency and energy efficiency grade for flat panel televisions>

[12] http://www.energylabel.gov.cn

[13] http://www.etao.com

How do Housing Energy Efficiency Standards in Japan affect the choice of equipment?

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Abstract

Energy consumption of Japan's civilian sector (commercial and residential) has increased greatly compared with other sectors (industrial and transportation), and various countermeasures have been sought. Before now, measures for the residential sector included appliance energy efficiency standards (Top Runner Standards) and housing energy efficiency standards. The Top Runner Standards have improved the energy efficiency of the subject equipment, which includes room air conditioners, refrigerators and TVs. Since housing energy efficiency standards were set in 1980, they have been revised several times. In October 2013, they were changed to a system of standards that evaluates a house's annual primary energy consumption for heating, cooling, water heating, ventilation, and lighting.

The main effect expected from enforcing housing energy efficiency standards is a decrease in the number of products with poor energy efficiency. On the other hand, it is not a mechanism for eliminating individual products, but rather, aims to improve the energy efficiency of the whole dwelling unit. Therefore the mechanism allows much flexibility of design.

In this paper, we explain the standards system, evaluation methods, and the relation to the Top Runner Standards for the housing energy efficiency standards. Also, to consider the impact of Japan's housing energy efficiency standards on choice of equipment, we examine the effect of the standards on both individual equipment and on the housing market as a whole.

Introduction

Japanese energy efficiency policies for housing and other buildings have evolved around the Act on the Rational Use of Energy in Japan (henceforth, "Energy Conservation Act"). Pursuant to the Energy Conservation Act, energy efficiency standards for housing and buildings were implemented in 1980. Since then, these standards have been revised and strengthened several times, with the most recent revision in 2013. In order for government to confirm building energy efficiency levels, as well as equipment operation and maintenance conditions, it has been made obligatory to report equipment specifications for buildings larger than a certain scale (300 m^2), but it is not required that building envelope performance or primary energy consumption meet minimum energy efficiency standards. (In cases where energy efficiency performance is extremely poor, the government sometimes provides guidance.) Japan may be the only developed nation that operates housing and building energy efficiency standards as voluntary standards. As is shown in Figure 1, the ratio of conformity to housing energy efficiency standards as of 2011 was about half.

Before now a variety of energy efficiency policies were taken but from 1990 on, civilian sector (commercial and residential) energy consumption is growing greatly compared to other sectors (industrial and transportation), so additional measures have been sought. One residential sector measure is energy efficiency standards for appliances (below, "Top Runner Standards"), which have improved the efficiency of energy consumption by equipment. As a further energy efficiency measure, according to the Japan Revitalization Strategy, announced by the Cabinet in June 2013, "by 2020 all new housing and buildings will be obligated to meet energy efficiency standards in stages." By 2020, it is planned that buildings with floor area 2000 m^2 or greater, 300 m^2 or greater but less than 2000 m^2, and less than 300 m^2, will be obligated to conform to energy efficiency standards in stages, starting with large-scale buildings. Investigations have begun aimed at developing levels, indicators, and targets of evaluation by which to judge conformity to standards. In this paper, we focus on energy efficiency standards related to housing (below, Housing Energy Efficiency Standards, or HEES), give an overview of the standards organization and evaluation methods, and examine the influence of introduction of HEES on equipment choices.

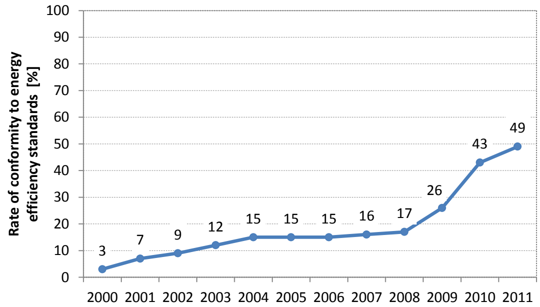
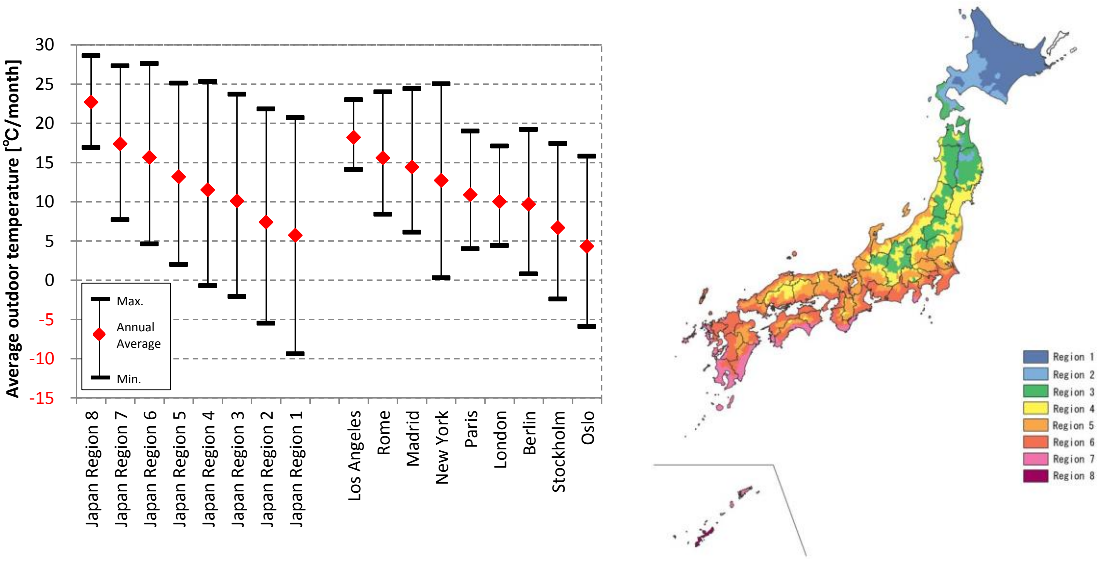


Figure 1. Change in rate of conformity to energy efficiency standards in housing
Source: Ministry of Land, Infrastructure, Transport and Tourism

Content of Housing Energy Efficiency Standards

Japanese climate and lifestyle characteristics

The average outdoor temperatures by month for Japan's regional divisions are shown in Figure 2. Figure 2(a) shows the minimum, maximum, and average values for monthly average outdoor temperature. As is shown in Figure 2(b), the Japanese archipelago spans a wide range from north to south, with varying climate conditions, from the coldest, Hokkaido, to the hottest, Okinawa Prefecture. In order to evaluate building envelope performance and equipment energy consumption appropriately, in the HEES, Japan is divided into 8 regions, with reference values set corresponding to representative climate conditions for each region. Comparing the minimum monthly outdoor temperatures, of the 8 regions, Regions 4 and 5 are similar to New York and Berlin, while Region 2 is similar to Oslo. Comparing the maximum monthly outdoor temperatures, Regions 6 through 8 are hotter than any of the European and US cities shown. Great differences in hot and cold extremes, and high relative humidity that makes heat protection measures necessary, can be thought of as Japanese climate characteristics.



(a) Average outdoor temperature (b) Japanese regional divisions

Figure 2. Comparison of monthly average outdoor temperatures for western cities and Japanese regional divisions.
Note: (a) shows minimum, maximum, and average monthly outdoor temperatures

In comparison to other countries, a noteworthy characteristic is the manner in which spaces are heated. In contrast to the typical method in cold regions of heating a large part of the whole house for long hours, in relatively warm regions, the predominant method is to heat only rooms while they are occupied. In that case, there is little heating of unoccupied rooms, such as hallways, entrance hall, bathrooms.

Housing Energy Efficiency Standards organization

HEES take as their object single dwelling units, and two standards are set, for envelope performance and for primary energy consumption. The envelope performance standard requires calculation of the dwelling unit's envelope performance based on specifying the envelope components, and this must meet reference values set for each region. The primary energy consumption standard requires that the dwelling unit's design primary energy consumption be calculated based on the specified equipment and appliances, and this must not exceed the reference primary energy consumption set for each region. The performance value calculated to judge envelope performance uses the same heating and cooling load conditions used to calculate heating and cooling design primary energy consumption. In this way, the system evaluates envelope performance and primary energy consumption uniformly.

Evaluation Method for Housing Energy Efficiency Performance

(1) Envelope Performance

The envelope performance standard has both an "envelope average thermal transmittance" and a "cooling period average solar radiation heat acquisition ratio" set for each region. The envelope average thermal transmittance is the sum of the heat losses from each part, such as ceilings, walls, and floor, divided by the sum of the area of each part. The cooling period average solar radiation heat acquisition ratio is defined as the sum of solar heat gains for each part for each direction divided by the sum of the area of each part, and is expressed as a percentage.

envelope average thermal transmittance U_A (W/m^{2}K)

$$U_A = \left(\sum_i^n \left(A_i \times U_{H,i}\right) + \sum_j^m \left(L_{F,j} \times U_{FH,j}\right)\right)/A$$

A_i : area of the ith envelope component, excluding parts like the foundation, that contact the ground (below, "foundation") (m^2)

$U_{H,i}$: thermal transmittance of the ith envelope component, accounting for mitigation of heat conduction due to temperature differences with adjacent spaces (W/(m^{2}K))

n : number of envelope components, excluding foundation

$L_{F,j}$: length of the outer perimeter of the jth foundation component (m)

$U_{FH,j}$: thermal transmittance of the outer perimeter of the jth Foundation component (W/(mK))

m : number of foundation components

A : envelope total area (m^2)

Cooling period average solar radiation heat acquisition ratio η_A(-)

$$\eta_A = \sum_i^n \sum_j^m \left(A_{ij} \eta_{C,ij} \nu_{C,j}\right)/A \times 100$$

A_{ij} : area of the ith envelope component in the jth direction (m^2)

$\eta_{C,ij}$: cooling period solar radiation heat acquisition ratio of the ith envelope component in the jth direction

$\nu_{C,j}$: direction coefficient for the heating period

A : envelope total area (m^2)

m : number of directions

n : number of envelope components

(2) Primary Energy Consumption

End uses subject to evaluation of primary energy consumption are space heating and cooling, water heating, ventilation, and lighting. Because household electrical appliances and cooking are not included as building equipment, a fixed value that depends on the floor area and number of family members is prepared. Also, if there is an on-site electric generating system, such as a photovoltaic system or a cogeneration system, then of the electricity generated, only the electricity consumed on site is evaluated. Because the calculation of primary energy consumption for each end use is very complicated, a calculation program has been published online[1] as a calculation tool.

Design primary energy consumption E_T (GJ/y)

$$E_T = (E_H + E_C + E_V + E_L + E_W - E_S + E_M) \times 10^{-3}$$

E_H : space heating design primary energy consumption (MJ/y)
E_C : space cooling design primary energy consumption (MJ/y)
E_V : mechanical ventilation design primary energy consumption (MJ/y)
E_L : lighting design primary energy consumption (MJ/y)
E_W : water heating design primary energy consumption (MJ/y)
E_S : amount of reduction in design primary energy consumption due to use of energy efficient equipment (MJ/y)
E_M : electrical appliances, cooking and other primary energy consumption (MJ/y)

As stated above, the designer must make sure that the sum of design primary energy consumption for each end use evaluated does not exceed the total reference primary energy consumption. Reference values of reference primary energy consumption for each end-use are not set, so even if equipment for a particular end-use has large primary energy consumption, by using more energy efficient equipment for another end-use, the reference primary energy consumption standard can be met (sample calculation below).

The design primary energy consumption is calculated based on the floor area of the evaluated dwelling unit. For calculation, rooms are divided into main living rooms (living, dining, kitchen), other living rooms (such as bedrooms), and non-living rooms (such as hall, bathroom, toilet), to reflect the different equipment conditions and occupancy conditions of various rooms in the calculations. For loads that vary with the number of occupants, such as water heating load, lighting illumination time, and local ventilation usage time, an assumed number of occupants is set for evaluation purposes, according to the total floor area. Because the number of occupants is uncertain at the time of reporting or application, and the calculation is a benchmark that evaluates the dwelling unit's structure and equipment, the method of assuming the number of occupants based on the total floor area is used in the evaluation.

In order to evaluate equipment energy performance appropriately, the assumed occupants' living schedules and operating conditions, such as temperature settings, are set for each day and time of day, according to living patterns for work days and non-work days. In particular, because heating and cooling operation modes generally vary by region and by equipment in use, the operating conditions are set depending on the equipment in use, with operation mode is set as whole house continuous operation (the whole house is conditioned for long hours continuously), partial continuous operation (living rooms only are conditioned continuously), or partial intermittent operation (rooms are conditioned only when occupants are present).

Methods to evaluate energy performance of equipment have been set based on demonstration test results conducted by research organizations. For each end use evaluated, energy efficiency measures are set, and designers can easily use a program to calculate the effects of energy efficiency measures they choose.

[1] http://house.app.lowenergy.jp/

As for calculating primary energy consumption, loads are set corresponding to factors such as the subject dwelling unit's envelope performance, the dwelling unit scale, and installation of any equipment to contribute to cutting the load (for example, solar water heaters and hot water conservation apparatus). Energy consumption is calculated from the efficiency of energy consumption by each day or each hour. Primary energy consumption is calculated as an annual value that sums up energy consumption by hour or by day. Table 1 shows the equipment types and energy efficiency measure categories for each end use currently subject to evaluation.

Table 1. Input conditions and evaluated categories for calculating primary energy consumption

Evaluation Category			Input Category
regional division			・regional division (climate conditions)
building conditions			・floor area (main living rooms / other living rooms / non-living rooms)
equipment conditions	heating /cooling	load calculation conditions	・envelope average thermal transmittance ・average solar radiation heat acquisition ratio ・presence / absence of heat storage site (contributes to decreased heating load) ・presence / absence of windows that open in summer (contributes to decreased cooling load)
		evaluated heating equipment	・ducted central air conditioner ・room air conditioner ・FF (forced draft balanced flue) type heater ・panel radiator ・hot water floor heating ・fan convector ・electric resistance floor heating ・electric storage heater ・floor heating with room air conditioner
		evaluated cooling equipment	・ducted central air conditioner ・room air conditioner
		energy efficiency measures	・use of high efficiency equipment ・variable capacity compressor (room AC)
	ventilation	evaluated equipment	・ducted type 1 ventilation equipment ・ducted type 2 or type 3 ventilation equipment ・ductless type 1 ventilation equipment ・ductless type 2 or type 3 ventilation equipment
		energy efficiency measures	・electricity consumption and air volume ・duct diameter ・motor type ・use of heat recovery ventilation equipment
	water heating	evaluated equipment	・gas water heater (conventional / condensing) ・oil water heater (conventional / condensing) ・electric water heater (resistance type / heat pump type) ・hybrid electric heat pump and gas water heater
		energy efficiency measures	・use of high efficiency appliance (input energy use efficiency) ・use of solar water heater ・plumbing method ・presence / absence of hot water-saving valve ・presence / absence of insulated bathtub
	lighting	evaluated equipment	・incandescents ・everything but incandescents
		energy efficiency measures	・presence / absence of distributed multi-light method use (main living rooms) ・dimmers (main living rooms / other living rooms) ・occupancy sensor (non-living rooms)
	electricity generation	evaluated equipment	・solar electric generating system (capacity, type of array, orientation, installation angle) ・combined heat and power system (gas engine, solid oxide fuel cell, polymer electrolyte fuel cell）

Primary Energy Consumption Calculation Results

Using the calculation conditions shown in Table 2, we can understand the degree to which equipment effects primary energy consumption. For this case the house is a two-story 120.08 m^2 house in Region 6, which corresponds to Tokyo. The envelope performance and equipment were specified at levels needed to attain the standard (henceforth called, "standard equipment specifications"). It must be noted that, because the primary energy consumption of the equipment will vary with the region and other factors, the results shown here are simply one example.

Table 2. Standard equipment specification calculation conditions

		Equipment specification
region		・Region 6 (includes to Tokyo, Osaka, Nagoya and Fukuoka)
building		・floor area 120.08 m^2 (principle living rooms 29.81 m^2, other living rooms 51.34 m^2, non-living rooms 38.93 m^2)
envelope performance		・envelope heat loss per unit temperature difference 279.8 W/K ・solar radiation heat acquisition per unit solar irradiance: cooling period 6.42 W/(W/m^2), heating period 12.37 W/(W/m^2) ・not using cross ventilation ・not using heat storage
equipment	heating	・for room-by-room intermittent operation, room AC (efficiency: average value) ・for room-by-room continuous operation, FF-type heater (efficiency 86.0%)
	cooling	・for room-by-room intermittent operation, room AC (efficiency: average value)
	ventilation	・specific fan power: 0.3W/(m^3/h) ・air exchange rate: 0.5 ACH ・heat exchange: not used
	water heating	・gas water heater (with reheating): efficiency 78.2% ・plumbing: branch method ・water-saving appliances not used. ・high insulation bath tub not used
	lighting	・main living rooms, other living rooms: use incandescents in part of house ・no use of incandescents in non-living rooms

Figure 3 shows primary energy consumption by type of heating equipment. The reference value is set depending on the operation method. Room air conditioner and electric resistance floor heating use room-by-room intermittent operation, while panel radiator and electric storage heater use room-by-room continuous operation. Note that other than the heating equipment categories shown on the vertical axis, all other categories are the standard equipment specifications shown in Table 2. For room-by-room intermittent operation the primary energy consumption is 81.3 GJ/y, and the consumption decreases if a high efficiency air conditioner is used. On the other hand, if electric floor heating is used the design primary energy consumption is 102.6 GJ/y, an increase of 21.3 GJ/y over the reference value. For room-by-room continuous operation the primary energy consumption reference value is 109.9 GJ/y, and the consumption decreases to 104.8 GJ/y if panel radiators with a condensing gas water heater are used. On the other hand, if electric storage heating is used the design primary energy consumption is 156.2 GJ/y, an increase of 46.3 GJ/y over the reference value.

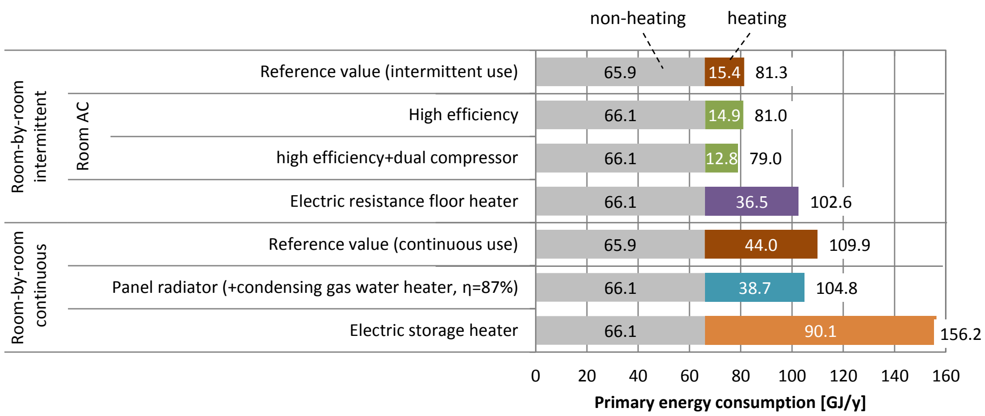


Figure 3. Primary energy consumption by type of heating equipment

Figure 4 shows primary energy consumption by type of water heating equipment. Other than the water heating equipment categories shown on the vertical axis, all other categories are the standard equipment specifications shown in Table 2. The reference value varies depending on the number of householders, which for our standard dwelling unit of 120.08 m^2 corresponds to 4 people. By using a high efficiency water heater, such as condensing gas or oil water heaters or an electric heat pump water heater, primary energy consumption is less than the reference value. On the other hand, if an electric resistance water heater is used the design primary energy consumption is 116.2 GJ/y, an increase of 34.9 GJ/y over the reference value.

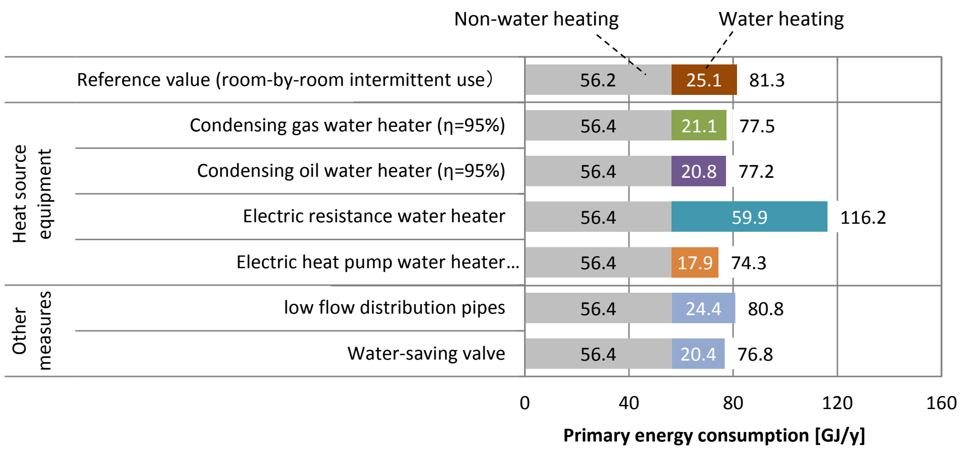


Figure 4. Primary energy consumption by water heater type

Figure 5 shows primary energy consumption by type of lighting, and Figure 6 shows primary energy consumption when solar electric generation or combined heat and power systems are installed. The standard is calculated for the case using incandescent lighting in principle and other living rooms, as shown in Table 2, so when incandescents are not used the design primary energy consumption is 77.4 GJ/y, less than the reference value. When the distributed multi-light method is used with dimmer control, lighting becomes even more energy efficient. When a 2 kW solar electric system is used, the design primary energy consumption is 69.6 GJ/y, and when a SOFC is used it is 68.5 GJ/y, decreases of 11.7 GJ/y and 12.8 GJ/y respectively.

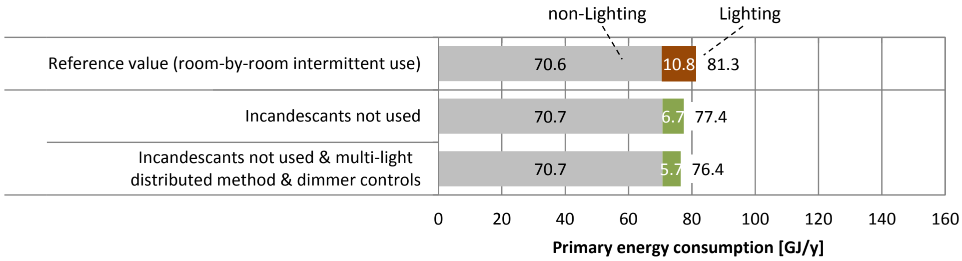


Figure 5. Primary energy consumption by lighting type

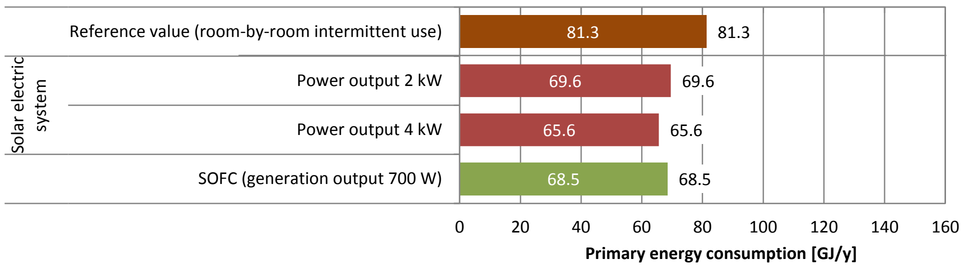


Figure 6. Primary energy consumption with solar electric or combined heat and power systems

Various choices of equipment become possible because, as shown above, the efficiency of equipment by end use and energy efficiency measures are comprehensively evaluated based on constraints that decrease design primary energy consumption below reference primary energy consumption. Examples of choices of equipment combinations with design primary energy consumption lower than the reference primary energy consumption are shown in Figure 7. When incandescents are used, lighting energy consumption increases, but by using a high efficiency gas water heater that decreases water heating energy consumption, the designed value is less than the reference value of primary energy consumption. Also, when electric resistance floor heating is used, heating energy consumption is more than twice the reference value, but by combining a solar electric system, a high efficiency water heater, and hot water-saving valves, the design primary energy consumption becomes less than the reference value. Further, when an electric storage heater is used, as shown in Figure 3, heating energy consumption is 46.3 GJ/y higher than the reference value, but by improving insulation performance to decrease the heating load, the increase in heating energy consumption can be curbed, and by using a high efficiency water heater, design primary energy consumption can be brought below the reference value.

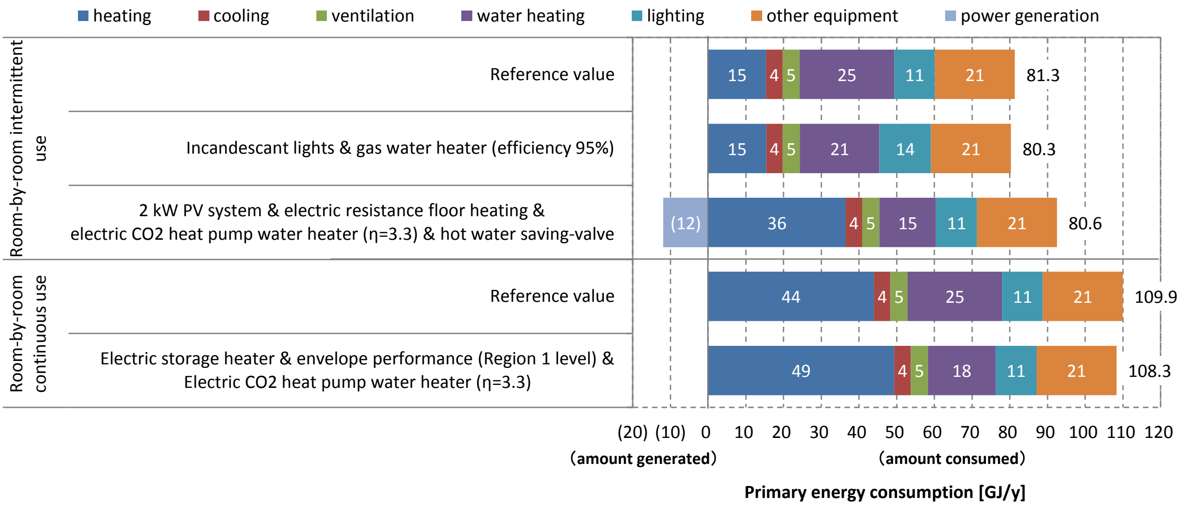


Figure 7. Examples of specification combinations that meet the reference primary energy consumption

Influences on equipment choice

First, we explain the Top Runner Standards (TRS) and Housing Energy Efficiency Standards (HEES), which are representative of policies for the residential sector.

・HEES are characterized by addressing energy efficiency of the whole dwelling unit, allowing for various choices of equipment, while TRS are characterized by aiming to improve efficiency of specific, targeted equipment.
・TRS are covered by HEES, and are expected to lead to higher efficiency for air conditioners, electric heat pump water heaters, and other targeted equipment, but not for equipment that is not targeted, such as electric storage heaters and electric resistance water heaters.
・HEES apply to new construction. It is not known whether they influence choice of high efficiency equipment at time of replacement, but for targeted equipment TRS address all products on the market so both new installations and replacements are covered.
・Appliances outside the scope of HEES, such as refrigerators, are targeted by TRS.

In this way, the TRS and HEES have a complementary relationship. In this section, we focus on the choice of equipment that is a characteristic of HEES. In particular, we examine the impact on four individual equipment types, electric storage heater, electric resistance water heater, gas condensing water heater, and lighting, and also on the effect on the housing market.

Effect on individual equipment

(1) Electric storage heater

Electric storage heaters generally operate continuously 24 hours per day and are very comfortable due to radiant heating. In Japan they have a high penetration in cold climate regions. However, because the heat is due to Joule heat, these appliances consume a lot of energy (see Figure 3). With the introduction of HEES, the constraint on primary energy consumption was initiated, and when an electric storage heating is used, it is also necessary to improve insulation performance and combine with a solar electric system, as shown in Figure 7. Therefore, electric storage heaters will probably continue to be installed by some households that prioritized comfort, but as an overall trend will probably decrease in use. On the other hand, as a measure to promote the energy shift to electricity, if preferential tax treatment or other policies are implemented for electric storage heaters, then they may spread.

(2) Electric resistance water heater

There are two types of electric water heaters on the market: electric resistance water heaters and electric heat pump water heater (CO_2 refrigerant). From their first appearance in April 2001 until 2010, the number of electric heat pump water heaters sold increased rapidly, but since the Great East Japan Earthquake in 2011 the number of units shipped has decreased. Since the introduction of the electric heat pump CO_2 refrigerant water heater, sales of electric resistance water heaters have fallen by half, from more than 200,000 to around 100,000 units per year. In 2012 the penetration of electric water heaters was 14%, with an estimated 7,700,000 units in service (14% of about 55 million households). In the roughly 10 years since the introduction of the electric heat pump CO_2 refrigerant water heater the cumulative number shipped is about 3,600,000, a 47% share, so electric resistance water heaters make up about half the electric water heaters installed.

Due to the introduction of HEES, as shown in Figure 4, if an electric resistance water heater is used, to make the design primary energy consumption conform to the reference primary energy consumption, over 30 GJ of countermeasures must be carried out. For example, if a solar electric system is installed, even with a 4 kW system only a 15 GJ reduction is achieved, so the standard is not met. As of 2012 there has been a fixed demand for about 100,000 electric resistance water heaters per year, but, unlike the electric storage heater, they have little merit with respect to comfort or other amenities, so their demand is expected to decrease in the future. Also, in April 2014, a Top Runner Standard was implemented for the electric heat pump CO_2 refrigerant water heater, so further progress in improving it's efficiency are expected (Figure 8).

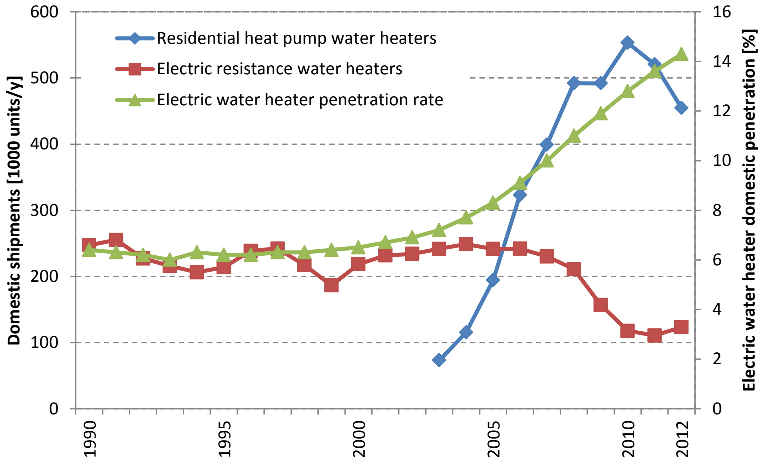


Figure 8. Electric water heater domestic numbers shipped and penetration rates
Source: numbers shipped, Japan Refrigeration and Air Conditioning Industry Association; penetration rate, Jyukankyo Research Institute Inc.

(3) Gas condensing water heater

With the introduction of the HEES the numbers of houses using energy efficient gas condensing water heaters is expected to increase relative to conventional gas water heaters. However, when the current situation in Japan is considered, the industry is promoting switching from conventional to condensing gas water heaters, so the impact of the HEES on switching to gas condensing water heaters is thought to be small. Note that gas water heaters are targeted under the Top Runner Standards, but target values have not been revised recently.

(4) Lighting

By 2013, all major domestic manufacturers of incandescent bulbs had ended production, and the diffusion of high efficiency lights such as compact fluorescent lamps and LED lighting had progressed. In particular, Table 3 shows that in 2013, 43 million LED lamps were sold for use in lighting. The data are not known for all categories, so it is not an exact comparison, but considering that a total of 52 million lamps were shipped in 2009, we can infer that LED lamps have spread rapidly.

Improving efficiency and decreasing cost of LED lighting is progressing, and they will continue to spread unrelated to the introduction of HEES. On the other hand, it is expected that there will continue to be certain niches where incandescents are preferred, but through introduction of HEES their overall use will decrease.

Table 3. Change in number shipped of lamps for use in lighting

Type of lamp	2009	2013
General use light bulbs	13,914	-
CFL lamps	38,490	-
LED lamps	-	43,159
Total	52,404	43,159

Note: Also includes non-residential uses. "-" = statistics unavailable. Units: 1000 lamps.
Source: Ministry of Economy, Trade and Industry, equipment statistics

Effect on the housing market

In FY2013 housing starts in Japan were generally split one to one between new construction of detached houses and apartments. Envelope performance and heating and cooling loads differ for detached houses and apartments, as do limiting conditions, such as the areas available for installing equipment. For example, it is relatively easy to put solar electric systems and combined heat and power systems on in detached houses, and because the heating load is smaller for apartment buildings floor heating can be easily used. The choice of equipment depends on the type of building.

Until now it was difficult to objectively evaluate choices of equipment of varying types for varying end uses, such as room air conditioners, hot water floor heat and gas water heaters. The introduction of HEES has made it possible to compare these using primary energy consumption. Design support tools and services to investigate conditions that meet the reference primary energy consumption are likely to be developed by private sector businesses. Due to these standards, designers who have previously been indifferent toward energy can offer their homebuilding clients highly energy efficient, optimal equipment and envelope performance.

On the other hand, at the time that conformity to standards became obligatory, there was concern that HEES would be expected to be operated as a MEPS, and in that case there would be many dwelling units with efficiencies concentrated around the standard value. Investigations aimed at translating the obligation of conformity to HEES into reality have begun, but in order that the optimal equipment not be chosen simply because it conforms to the primary energy consumption standard, it is also important that there be incentives to encourage more efficient dwellings. There are plans to support Zero Energy Buildings and Zero Energy Houses, for which targets have been set as guiding standards. In addition, because HEES are regulations for new construction and the building itself lasts 30 years or longer while the equipment generally has a 10 to 15-year lifetime, it is also important to have measures that encourage choice of energy efficient equipment at the time of replacement.

Conclusion

In this paper, we have examined the influence of the introduction of HEES on choices of equipment. As a major effect of HEES, we expect use of products with poor energy efficiency to decrease. However, HEES is not a mechanism for doing away with individual products. Rather, if products with poor energy efficiency are used, additional energy efficiency measures must be taken to allow for the use of that product. HEES is a mechanism that aims to increase efficiency of the whole dwelling unit, with many degrees of freedom in design. Furthermore, the Top Runner Standards focus on increasing the efficiency of individual appliances, and together the HEES and TRS have a complementary relationship. Their effects on the individual equipment examined here is as follows.

・Because use of an electric storage heater makes it difficult for design primary energy consumption to be less than reference primary energy consumption, these are expected to continue to be used by certain households that value comfort, but in general the trend will be for their use to decrease.

・Use of an electric resistance water heater makes it difficult for design primary energy consumption to be less than reference primary energy consumption, but unlike the electric storage heater, it does not have particular merit for comfort or other amenities, so its use is expected to decrease in the future.

・Condensing gas water heaters are becoming the de facto standard, so the introduction of HEES there would not be expected to cause a major change in this market.

・LED lighting will continue to penetrate unrelated to HEES. However, it is likely that there will continue to be a fixed demand for incandescents by those who prefer them, but introduction of HEES will lead to a decreasing trend in use of incandescents.

Further, while it is hoped that residents can participate actively in the housing market and decide about the choice of equipment, there is also concern that passive choices of equipment that barely conform to the reference primary energy consumption will take place. It is important to pay close attention to future trends after introduction of HEES.

Acknowledgements

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Impacts of the EU's Ecodesign and Energy/Tyre labelling legislation on third jurisdictions

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Abstract

This paper presents the findings of an investigation into equipment energy efficiency policy measures, and explicitly Minimum Energy Performance Standards (MEPS) and energy labels, in countries outside the EU. The evidence draws upon an in-depth literature and website review, stakeholder survey and analysis of standards and labelling databases. Detailed information was gathered on the equipment energy efficiency standards and labelling programmes in place in forty eight non-EU countries and less detailed information on a great many others. From this it is established that there are 45 countries, excluding the 28 EU Member States, that have adopted MEPS and 59 non-EU countries that have adopted energy labelling for energy using equipment. Overall there has been a 17 fold increase in the number of countries having comparative energy labels since 1990 and a nine fold increase in the number with MEPS. Countries with MEPS in place account for 91% of global GDP and 73% of global population. In 2013, there were at least 548 energy performance standards and 541 comparative energy labelling regulations in place outside of the EU covering 55 different product types, although all these programmes were first promulgated for household equipment.

The evidence gathered in this analysis reveals extensive, but often passive, EU policy influence in 3rd countries; in particular in the design of energy labels. Out of 59 non-EU countries that have adopted equipment energy labelling schemes, half of them (53%) have adopted designs that have fully or partially emulated the EU energy label. There has also been strong European influence on international test procedures, although international influence has equally applied to European test procedures in this regard. There is much less evidence of international influence from EU MEPS although the influence appears to be increasing. On the other hand some EU practices with regard to the design of MEPS were originally developed in the US regulatory process.

The analysis shows that international cooperation on equipment energy efficiency standards and labelling has contributed to delivering much greater energy, economic and environmental savings than would have occurred otherwise. Willingness to share programmatic experience, learn from and emulate the successes of other programmes is an essential component of the product policy achievements made so far and this has led to the rapid promulgation of equipment energy efficiency measures round the world. The paper concludes with recommendations on how this can best be facilitated in the future.

Introduction

This paper presents the findings of an investigation into equipment energy efficiency policy measures, and explicitly Minimum Energy Performance Standards (MEPS) and energy labels, in countries outside the EU [1]. The principal aim of the work is to establish the degree to which the corresponding EU policy measures (Ecodesign and energy labelling) have influenced the policies set in third countries, but also to consider the degree to which third country policies have influenced those in the EU. The work was funded by the European Commission.

The evidence presented in this paper is based on a literature review and stakeholder discussions. This evidence was used to review and update the CLASP database [2], which is an extensive database of equipment energy efficiency standards and labelling policy measures in place around the world. The reviewed and updated data was then used for the analysis presented in this work. Through this work it has been possible to gather considerable detailed information on equipment energy efficiency standards and labelling programmes in place in forty eight countries outside the EU. Information has been gathered in less detail on a great many other economies. From this analysis it has been established that there are 45 countries, excluding the 28 EU Member States, that have adopted MEPS and 59 non-EU countries that have adopted energy labelling for energy using equipment (Figure 1)[1].

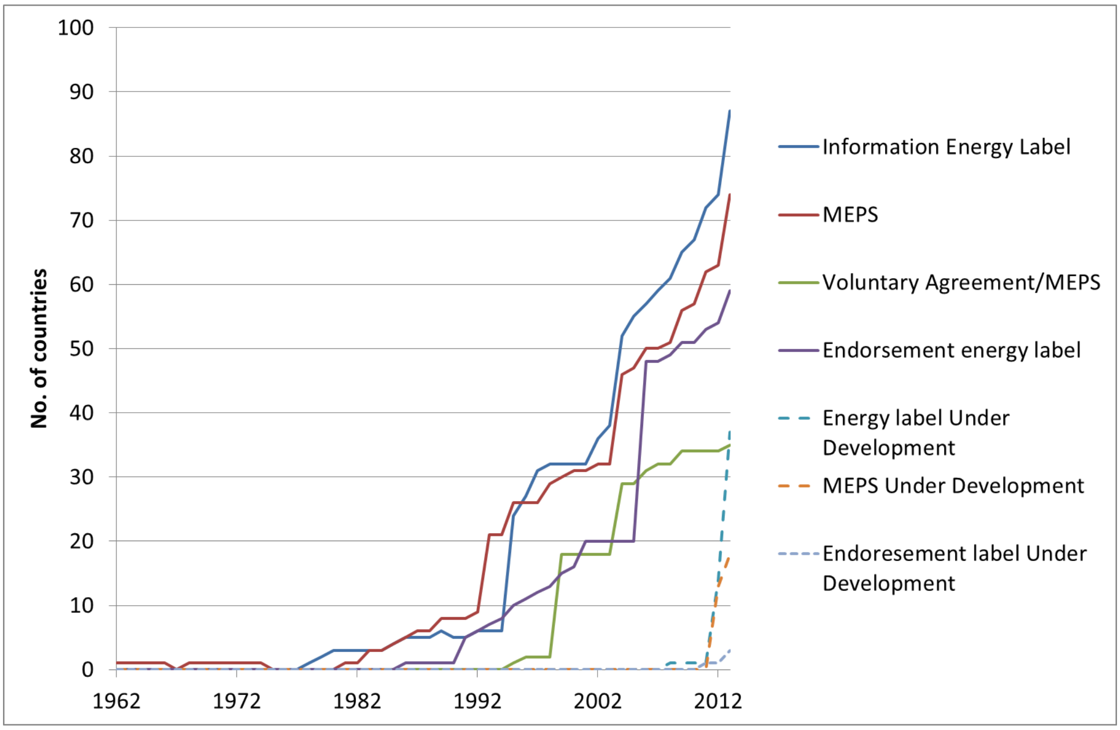

Figure 1: A timeline of international equipment standards and labelling policy implementation

The most detailed data on the specific regulations in place was entered into a database for the following countries:

Argentina, Australia, Brazil, China, Egypt, Ghana, India, Indonesia, Japan, Jordon, Kenya, Korea, Mexico, Nigeria, Philippines, Russia, South Africa, Tunisia, Turkey, USA

The very first equipment energy efficiency regulatory requirements may have been applied in Poland in the 1960s, but the first labels were applied in Canada in 1978. Since that time there has been a proliferation of standards and labelling requirements around the world with more specifications being adopted each year. Including the EU Member States, the number of countries with comparative energy labels in place for one or more energy using product[2] reached eighty seven by 2013. This represents an increase of 1740% from 1990 (5 countries) and a 281% increase from 2000 (31 countries). The number of countries with endorsement labels in place for one or more products reached 54 (up from 1 in 1990 and 16 in 2000). Regulations setting some form of minimum energy efficiency requirement for one or more energy using, or related, products have been adopted by 73 countries as of 2013. This represents a nine-fold increase from 1990 (8 countries) and a more than two fold increase from 2000 (31 countries). Countries with MEPS in place account for 91% of global GDP and 73% of global population, while those who have implemented energy labels account for 93% of global GDP and 75% of global population. This process continues and some 37 countries who

[1] Another study [3] conducted independently but in parallel to the work reported in this paper found very similar results regarding the adoption of MEPS and labelling worldwide.

[2] The scope considered in this paper is confined to energy efficiency standards and labels that apply to any tradable energy using or related products except those concerned with transportation.

have not had such policies in place previously are now known to be developing energy labelling along with 18 countries who are developing MEPS and 3 endorsement labels.

Just as the number of countries with equipment energy efficiency standards and labelling has increased, so has the range of equipment types subject to such regulations. In 2013, there were at least 548 energy performance standards and 541 comparative energy labelling regulations in place outside of the EU, EEA and accession states covering 55 different product types. These products cover equipment destined for residential, commercial and industrial applications and are responsible for a large proportion of all energy use in these sectors.

The influence of EU policy measures

If the EU, EEA and Accession states are considered as a whole, their equipment energy efficiency regulations account for 4% of the total number of comparative energy label regulations, 7% of the endorsement labels and 6% of the minimum energy performance standards regulations implemented in the world. The EU also accounts for a greater share of all voluntary agreements. However, the influence of EU policy measures on standards and labelling extends far beyond its borders.

The evidence gathered in this project implies extensive EU policy influence in 3rd countries, in particular in the design of the energy label. Out of 59 non-EU countries that have adopted equipment energy labelling schemes, half of them (53%) have adopted designs that have fully or partially emulated the EU energy label (Figure 2). This includes major economies such as Brazil, China, Korea, Russia and South Africa as well as EU accession states and many others including most South American countries, many North African countries and several countries in the Middle East. The timeline for energy labelling supports the assumption of EU influence as countries that adopted the labels earlier than the EU are of a different design.

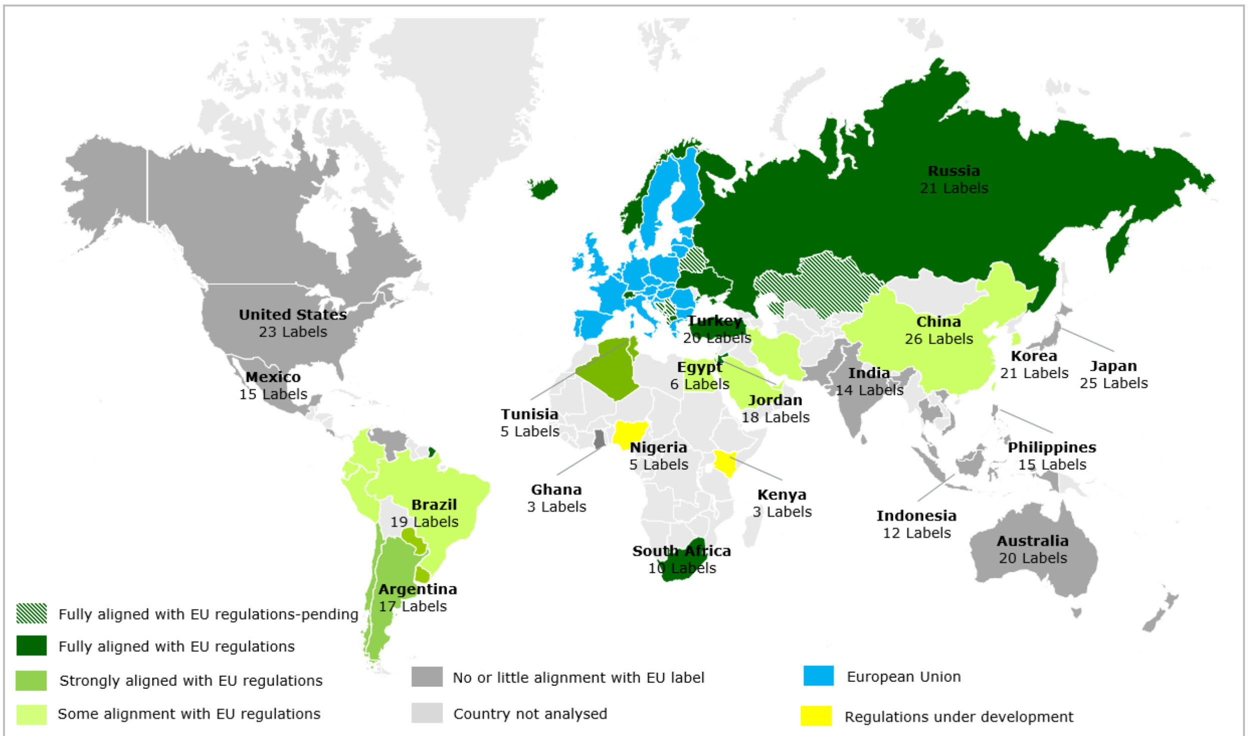

Figure 2: Countries with Energy Labels and degree of alignment with the EU label

The share of global GDP accounted for by countries that have implemented equipment energy labels reached 93% in 2013 and the share of global GDP taken by those who have an energy label that is in some degree aligned with the EU's was 44% (Figure 3).

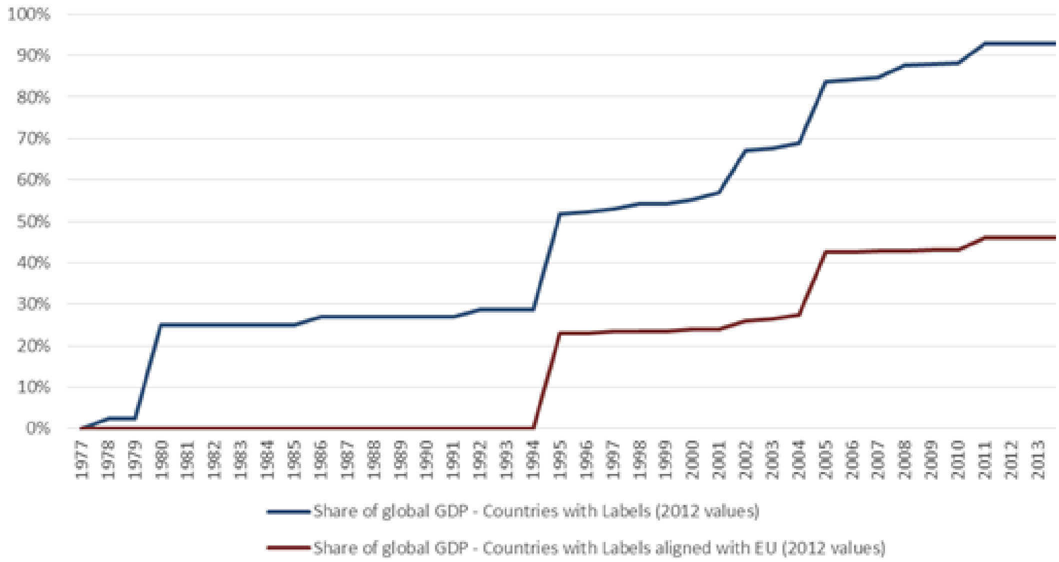

Figure 3: Countries with energy labels: coverage as a share of global GDP

Out of 45 non EU countries that have adopted MEPS, 23 (51%) have adopted MEPS for at least one equipment type that have fully or partially emulated the EU's Ecodesign requirements or its earlier MEPS, Figure 4.

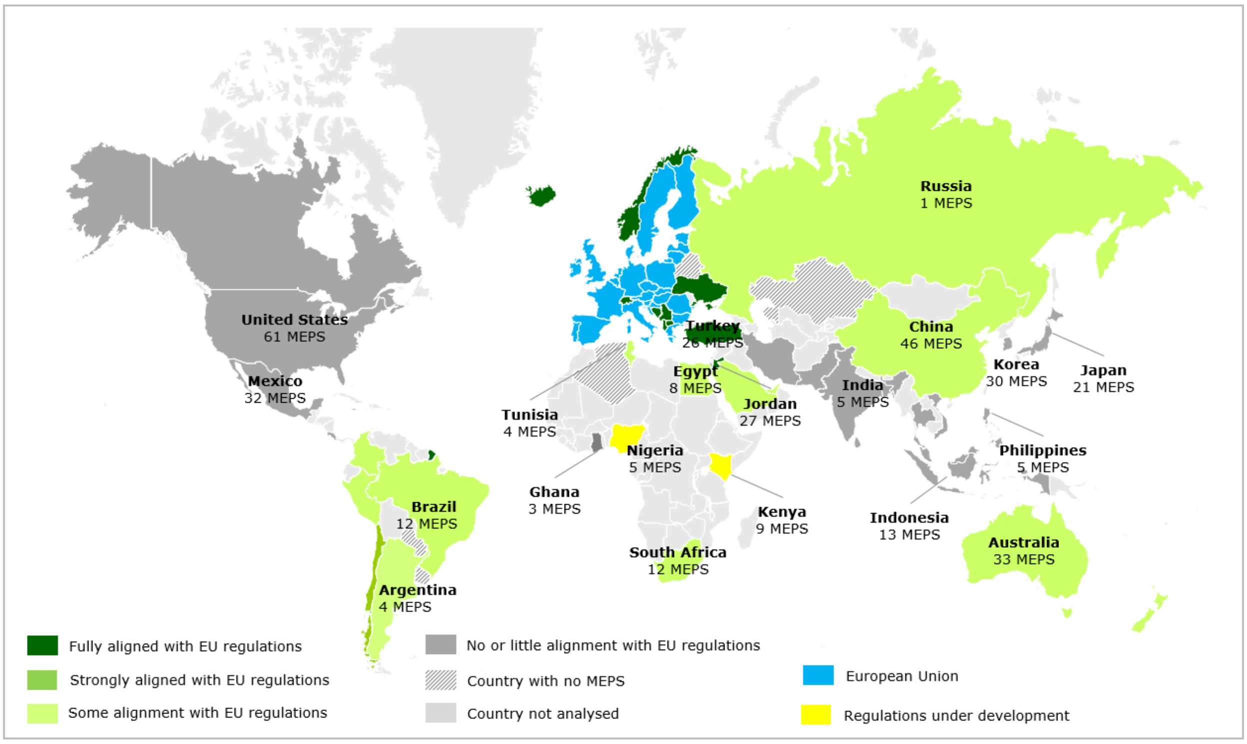

Figure 4: Countries with MEPS and Degree of Alignment with EU per Country

Figure 5 shows that the greatest alignment is in the area of test procedures. Outside of North America, the large majority of equipment energy performance test procedures in use are based on IEC/ISO/ITU test procedures. These are international test procedures but have been developed with strong input from EU national standards bodies (NSBs). The same NSBs also develop European standards through CEN/CENELEC/ETSI and these bodies have an arrangement with their international counterparts for each to adopt the other's standards through the Dresden and Vienna

Agreements. As a result European energy performance test standards are usually closely aligned with international test standards.

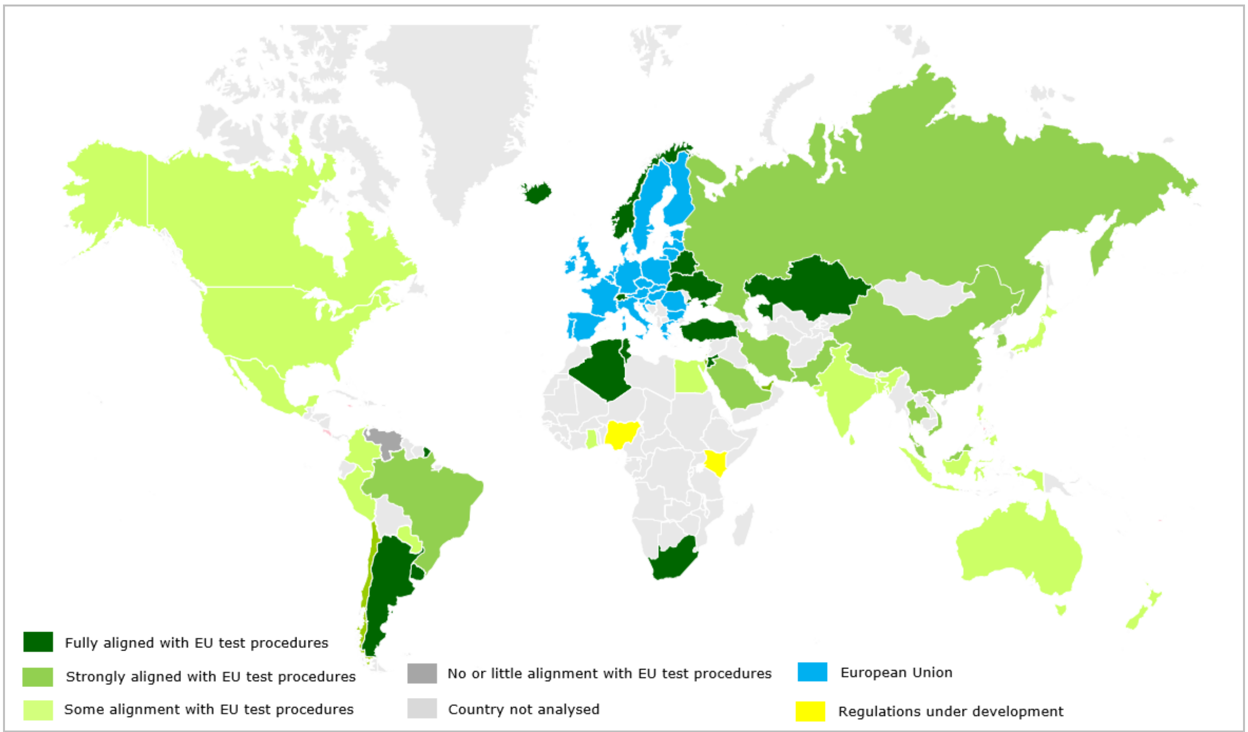

Figure 5: Similarities with EU test procedures

Motivation behind alignment

The motivation behind the degree of alignment seen and willingness by 3rd country regulators and standardisation agencies to consider adopting measures aligned with the EU varies. Many parties that were interviewed in relation to this work expressed a desire to avoid duplicating work and to thereby adopt measures that had been tried and tested in peer economies, such as the EU. Facilitation of trade is clearly another reason to consider alignment. Alignment of standards with other markets also avoids the situation where equipment which is below the standard in one market is dumped on the country market. As the EU is a large economy, it is an important market to consider when benchmarking standards[3]. The fact that the EU uses largely international test procedures undoubtedly facilitates this but also facilitates technology transfer. Producers in large exporter markets such as China aim to manufacturer equipment that meets EU efficiency and Ecodesign requirements to be able to export to the EU and thus the process of meeting EU specifications also facilitates the setting of domestic requirements that are potentially fully or partially aligned with the EU's. Laundry dryers provide a very clear example of where a third economy (USA) saw that the efficiency achieved by appliances on the EU market far exceeded that of the US market and is now building policies that emulate those of the EU. The use of common energy performance test standards also facilitates the adoption of common product platforms and types and hence lowers the transaction costs associated with technology and policy learning, and transfer. With globalisation of manufacturing, test standards developers tend to focus on the standards in the 'lead' economy for that product. The EU leads on home laundry equipment as discussed above, so this standard is followed by other economies, including Australia, China and US. On electric motors, the USA has been seen as the 'lead' economy and the EU has adopted IEC test methods and standards, which were strongly influenced by the USA.

[3] The IEA 4E and SEAD programmes have been mapping and benchmarking the energy performance of several products and their associated regulations.

An international symbol of energy efficiency

In the case of the European energy label, however, another element is in play. The EU energy label has become an international symbol of energy efficiency whose impact has extended well beyond the EU's boundaries and the appliance sector where it originated. In the EU itself the label motif of coloured stacked arrows ranging from A (green) to G (red) has been extended to buildings, tyres and cars and as to other types of consumer or commercial sector equipment (usually on a voluntary industry-association led basis). Elements of the same motif are found in energy labels adopted around the world, be it as direct or near direct copies (in South America, Africa, the Middle East, Russia and other former Soviet states), slightly amended versions (China, Hong Kong, Iran, Tunisia) or versions that copy the colour coding only (Korea, Chinese Taipei). Morocco is currently in the process of adopting equipment energy labels yet this has not prevented it from using the EU label as a symbol for efficiency for other energy end-uses as shown in Figure 6. The reason for the popularity of this motif is that it has been found to successfully communicate the key concept of energy performance relative to other equivalent products or end-uses on the market around the world. This has been confirmed whenever its ability to successfully convey these factors to consumers and other stakeholders has been tested via consumer and other market research (e.g. in China, the EU and Tunisia).

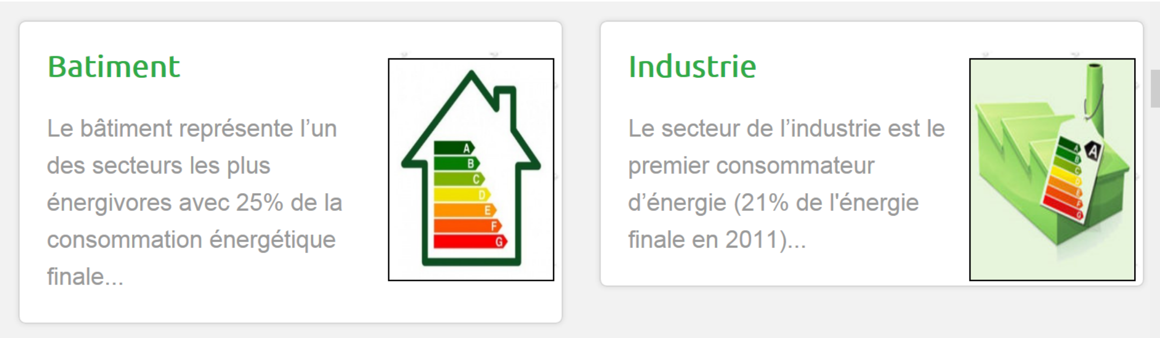

Figure 6. An example of how the European energy label motif is being used to promote the concept of energy efficiency in buildings and industry in Morocco. Source: http://www.aderee.ma/

The EU's label is not the only one to be emulated. The core aspects of the Australian energy label have been emulated in a number of markets and there are similarities between some aspects of the information energy labels used in Canada, Mexico, the Philippines and the USA. However, for the countries studied in this project it can be seen that the EU design is more often emulated than any other.

Influence of other programmes on the EU

The original work to develop energy labelling and MEPS in the EU was directly inspired by earlier US work and used many of the same techniques. The outcome in terms of labelling design was however quite different. Since that time, the EU has also joined forces with the US DOE and EPA to operate the international Energy Star programme (which originated as a domestic US programme in 1993). Less formal influence from 3rd county programmes has also been evident on specific EU policy measures. For example, work that had been done to benchmark the energy efficiency of room air conditioners and of their associated policy settings, was influential in encouraging a higher level of ambition in the EU energy label thresholds than had previously been envisaged. This was brought to light through the Ecodesign preparatory study process because it demonstrated that a peer economy had products of a significantly higher efficiency than the Best Available Technology on the European market at that time. A set of product case studies analysed in this report also show strong influence on EU policy measures by 3rd country activities for: electric motors, external power supplies and to a lesser extent, TVs.

Conclusions and recommendations

Evidence presented in this report, shows that international cooperation on equipment energy efficiency standards and labelling has contributed to delivering much greater energy, economic and environmental savings than would have occurred otherwise. Willingness to share programmatic experience, learn from and emulate the successes of other programmes is an essential component of the product policy achievements made so far and this has led to the rapid promulgation of equipment energy efficiency measures round the world.

When looking at how the transfer of best practice has occurred, the findings show it has often happened in an ad hoc manner. In the 1990s, there was very little international institutional support for technical and policy related support work for equipment energy efficiency best practice, yet it was in this period that the first work was done, usually by a small number of international consultants. Growing appreciation of the value of this work and the huge potential of equipment energy efficiency policy initiatives fostered the development of embryonic institutional activity in the late 1990s and early 2000s and has since led to further institutional development such that now there is:

- a dedicated NGO (CLASP) that supports international technical assistance on equipment standards and labelling
- a dedicated IEA implementing agreement (the IEA 4E [4]) which addresses energy efficiency cooperation in electrical equipment
- a global policy support framework in the Super-Efficient Appliance Deployment [5] initiative created through the Clean Energy Ministerial
- a dedicated UN agency supporting energy efficient lighting, in the form of UNEP's en.lighten programme [6]
- programmatic funding sources that can assist countries to develop equipment energy efficiency standards and labelling programmes and measures via the GEF, the World Bank Group, EBRD and other regional multilateral development banks
- bilateral programmatic funding to support equipment energy efficiency policy through international technical assistance programmes operated by the EU, USAID and State Departments, METI (Japan), RET in Australia and many others, including several EU Member State agencies

All these efforts provide support that, in many cases, is the engine for the transfer of best practice, however, there are certainly potential benefits from increasing the scale of these efforts.

The EU has been, and continues to be, a beneficiary of best practice developed in other economies, for example using analytical techniques that had been pioneered in the US MEPS rulemaking processes and the sharing of product performance, technology and cost data. It has also been a major source of innovation and best practice itself. Energy labelling is a clear example of this. Some of this emulation has occurred due to support from EU financed programmes but historically such support has been limited and emulation has occurred through processes that were not directly commissioned or supported by the European Commission or Member State agencies.

In response to a request from the European Commission the project developed detailed recommendations for specific aspects addressed in turn below (items 1 to 3). Following these, there are several additional recommendations for action that arose during research undertaken within the project. Sources for these included direct suggestions and requests from interviewees as well as observations drawn from the experience of the project team. These are included for consideration as they may complement or enhance the impact of recommendations under the three main requirements.

1. Methods and fora to increase international exchange about ongoing legislative processes between relevant administrations and governments with the aim to harmonise global legislation, including global standards, to establish a global, equal playing field for industry

There are many existing specialist fora through which the EU could work to increase international exchange on policies and technical issues. As resources to engage are limited, the following strategic approach is suggested for consideration:

1. Focus first on well-established international product policy fora that already attract policy-makers with whom the EU wants to engage. Priorities should certainly include **SEAD** and **IEA 4E**.
2. Develop **bi-lateral exchanges with priority economies**. Priorities can be set according to EU learning needs and also to achieve EU influence on policies in major trading blocks.
3. **Prioritise specific products** on which action is timely and necessary, working through whichever fora or activities will best achieve specific aims.
4. Consider supporting **NGO and technical Institutes** to achieve greater engagement with product policy issues within and outside of the EU. These types of organisation can achieve greater continuity than Commission officials, Member State policymakers and individual consultancies. Greater exchange between regions can also be facilitated through international NGOs and technical institutes if they can be more closely involved in the processes.

2. How to support European industry with information about planned and ongoing legislation in third jurisdictions?

Most industry associations have developed effective mechanisms to monitor regulatory developments and disseminate information to members. Improvement could be made, however, since the extent to which smaller businesses in particular exploit these mechanisms varies significantly between sectors.

The European Commission could usefully assist existing industry association communication mechanisms by providing authoritative information about third jurisdictions. This information could then be disseminated via well-established communication networks. This would ensure wider availability of well-founded information which might otherwise be derived from less well-informed and piecemeal research.

There are several ways in which the Commission could add value to this information for the benefit of European industry:

- First, the European Commission may have access to advanced information about policy development planning through its policy networks, and could judge on a case by case basis whether it was appropriate to make this known to the relevant industry sectors.
- Second, the Commission could provide expert insight into how the EU regulations differ or are similar to those from third jurisdictions in order to provide *initial indicative information* on regulations and requirements: of particular interest will be the indicative relative levels of minimum requirements, confirming which test methodologies are required to be used, specific requirements over and above any in force for the EU.
- Third, labelling and minimum standard requirements exist in some other regions for products which are not yet subject to EU requirements. This presents opportunities for developing support for future development of EU regulations in those directions, as well as initiating awareness and possibly preparation for compliance with these additional regulations wherever bilateral trade is likely.

To balance resources, this activity could focus on a smaller number of sectors, prioritised by factors such as: value of manufacturing in EU, potential for exports and proportion of SMEs in the sector; which could act to increase trade as well as bring environmental benefits. Such efforts should be done in manner that is complementary to existing databases, such as the CLASP database on standards and labelling programmes.

3. Methods and fora to increase the visibility of the European Union's Ecodesign and energy/tyre labelling legislation in third jurisdictions, and support third jurisdictions with the development of similar legislation

More could be done to make a one stop portal where information on all EU product policy, especially policy concerned with energy performance, is made available.

Some specific opportunities to address shortcomings and the broader dissemination of information on EU product policy are as follows:

a) While the Commission has begun to address some of these limitations by the initiation of projects to develop websites to provide data on some of these issues; these are still in their early stages and have a more limited scope than the actions described above. Thus, there is still potential to continue to improve access to and presentation of relevant information in a comprehensive format that is linked to the Commission's own site.
b) For Ecodesign studies and regulatory development processes of product groups identified as priorities for improved international harmonisation, representatives of target regions/economies could be invited to observe consultation fora, or perhaps join by webinar. Indeed a specific task to engage with such economies or bodies could be included in the task specification of contractors, and/or to brief suitable representatives via existing fora operating in those countries.
c) The Commission could present papers at a number of specific recurrent international events that are dedicated to, or have a strong focus on, equipment energy efficiency.
d) The Commission could sponsor an international journal or newsletter that carried updates on all equipment policy work carried out in the EU.

It is recommended that the Commission considers strengthening dissemination efforts via these or similar media and allocates resources that will enable a broader and more sustained communication about its programmes and their benefits.

To support third jurisdictions with the development of similar legislation the Commission could:

a) Develop regional engagement strategies and support mechanisms for the promotion of the development of product Ecodesign and labelling policies.
b) Consider supporting or working with specific Member State bilateral support initiatives addressing EU product policy topics.
c) Consider the creation of an "EU Energy Efficiency Ambassador" tasked with strengthening relations with markets outside the EU and improving communication, transfer of knowledge and knowhow regarding energy efficiency product policies between Europe and 3rd countries.

4. Emerging consensus on global 'ladders of performance standards' for various products, frameworks to enable greater harmonisation

The experience with electric motors and external power supplies has shown that where there is concerted action among governments it is possible to develop globally adopted menus of energy performance tiers for a product, which will have a common testing basis, common product categories and efficiency metrics and common energy efficiency thresholds. In general these would be developed through the international standards bodies such as ISO and IEC, although the external power supply case demonstrates that this is not always necessary if the relevant committee is not interested in working with product energy performance regulators. Ideally the standardisation process would have strong input from European standardisation experts with close ties to and knowledge of the objectives of the EU policy process. There are plenty of other product types that would benefit from the development of globally recognised energy performance tiers underpinned by common test methods and efficiency metrics. Some are quite advanced in developing such requirements but for most products work on performance tiers is yet to begin.

It is to address these kinds of concerns that the IEA/IEA4E/SEAD Community of Practice was established; however, this body would be likely to make much stronger progress were the Commission to become an active partner.

Whatever form it takes it is recommended that the Commission becomes an active player in the development of international dialogues among regulators, industry and standardisation bodies to promote greater alignment in test procedures, efficiency metrics and energy performance tiers.

5. Lessons from other countries programmes – improve coverage of standards and labelling policies

While many countries have emulated the appearance and sometimes (less frequently) the efficiency thresholds used in the European energy label, the EU is far from being a leading economy in terms of the product coverage of its energy label. The EU could learn from other economies that there is value to be derived in extending labelling (or at least mandatory disclosure of energy performance) to other sectors than just residential and consumer products. Other economies (e.g. Argentina, Australia, Brazil, Canada, China, Japan, Korea, Mexico, Philippines, USA amongst others) have labelling for one or more of: commercial AC equipment, commercial refrigeration equipment, compressors, high intensity discharge lighting, imaging equipment, inverters, industrial blowers, professional lighting applications, pumps (including general pumps, agricultural pumps, circulation pumps and pool pumps), motors and transformers. Currently the only non-residential sector product-group subject to labelling requirements in the EU is some types of lamps.

The expansion of the labelling products portfolio to include new product groups is also an important issue. Technologies like solar (thermal and PV) equipment, gas appliances and vehicles other than cars are some of the groups for which the EU still has an opportunity to develop policy measures. There are good examples in 3rd jurisdictions of policy implementation for these product types and the EU could benefit from information gathered in bilateral meetings and other forms of cooperation mentioned above, to accelerate European standards and labelling requirements for these products.

6. Cooperative work would be appropriate on energy using systems

No country has really attempted to use energy performance standards and labelling to apply to energy using systems unless they are sold as a packaged product. The EU is just now attempting to explore the boundaries of the extent to which systems level energy savings can be delivered via Ecodesign and labelling but this is innovative and there are likely to be significant limits to the ability of the policy instrument to access these savings. It is therefore recommended that the EU explores options for joint development work with 3rd country agencies on how best to establish effective policy instruments to promote energy efficient product systems.

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Proposal for an EU database of products regulated by the Labelling and the Ecodesign Directive

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Abstract

The market for energy-related products is characterised by a multitude of different product groups, manufacturers and suppliers and by products with ever-changing energy-related features. Gaining an overview of the products available on the market and its characteristics depicted at the EU Energy Label and regulated by the Ecodesign Directive would be of interest to several different stakeholders (European Commission, end-users, consumer associations, researchers, market-surveillance authorities etc.).

In the EU, there are several databases which compile differing amounts of data on general and energy-related product characteristics. But none of these meets the task to provide an overview of energy and further consumer relevant labelling and ecodesign information and requirements of all models of product groups regulated by EU Energy Labelling and Ecodesign Directive.

We propose a feasible solution with an EU product database that will make the key product data required under the Energy Labelling and the Ecodesign Directive publicly available. Manufacturers and suppliers will be required to enter the data printed on the label and on the data sheet required under the Energy Labelling Directive, as well as the key product data required under the Ecodesign Directive and the relevant provisions implementing this Directive. The database will merely be used to compile the data and make it accessible, whereas processing or evaluating the data, and presenting the information will be left to third parties. The database will be operated by the European Commission or an agency designated by the European Commission.

Introduction - Just another EU product database?

The market for energy-related products which are regulated by the EU Energy Labelling Directive and the Ecodesign Directive is characterized by a multitude of different product groups and manufacturers / suppliers and by products with ever-changing features, both technical and otherwise. However, there is no possibility yet to check or to compare energy and further consumer relevant labelling and ecodesign information and requirements of all models of a product group. As energy labelling and ecodesign information requirements made available by manufacturers or suppliers and retailers are, of course, limited to the models in their own range, it does not provide an overview of all models available on the European market. Gaining this overview of the regulated product groups in terms of their characteristics depicted at the EU Energy Label as well as their Ecodesign requirements would be of interest primarily to the European Commission, but furthermore to several different stakeholders as well.

The European Commission needs a reliable, complete and robust data basis in order to be able to develop and adapt requirements for labelling and ecodesign for product groups subject to such requirements.

End-consumers, i.e. private households, companies, and public-sector institutions would profit by such a data basis as it enables them to compare all available models within a certain product group in terms of product features declared on the EU energy label or regulated by ecodesign. Consumer associations could develop consumer counseling offers based on that data. Even rival companies on the market for products of the same category would benefit from the data basis that would create a level playing field. Furthermore, market surveillance authorities would profit by gaining an overview of models and features they have to enforce. Last but not least the data basis would allow to generate electronic labels and hence to reduce the expenditure of manufacturers and retailers.

The need for a product database is stressed by numerous current studies (e.g. [1], [2], [3]) and discussion papers (e.g. [4]), but the opinions about purposes, target groups, required data and design of the database diverge. Market surveillance authorities and the European Commission are regarded as main target groups besides private and professional consumers, manufacturers, decision-makers, researchers, NGOs, waste processing companies [1]. In [1] a registration of “information on chemical content, type of material ... and recyclability” is suggested in addition to labelling and ecodesign data. In [2] a wide range of further useful data that could be gathered in the database is mentioned, such as data needed for life cycle assessment, resource efficiency assessment and energy costs calculation. Krivosik [3] stresses, that the main purpose of the database is to support market surveillance by “a systematic and comprehensive collection of information” and by making it easier “to extract useful information, such as analysis of compliance rates for different product categories, identification of priority areas for future market surveillance plans, and follow-up to enforcement actions”. The authors of the Topten Discussion Paper [4] argue, that a product registration would lead to more ambitious labelling and ecodesign requirements and to market surveillance at a sufficient level regarding efficiency and energy consumption of products. Furthermore [4] mentions, that including “sales data into a database is a critical issue ... the wish for sales data could be realised on the longer term by adding a requirement for manufacturers to provide sales data to the database[...] Sales data would of course be confidential and public reports would only present aggregated data.”

This paper outlines a proposal for a feasible EU product database which would be as simple and effective as possible to implement and to operate. Therefore, in the first section we analyse characteristics of existing product databases using the categorisation scheme by SEAD [5] in order to explain, why existing product databases don´t meet the task to provide a market overview of all models regulated by the EU Labelling and Ecodesign Directive and their data relevant for labelling and ecodesign compliance. In the second section we draw up the key points concerning the implementation, structure and operation of a feasible EU product database. Although we consider the EU Commission as main target group of the product database, we point out in the last section advantages for various stakeholders who would benefit from the database.

Why existing product databases don´t meet the task

A report of the SEAD Policy Exchange Forum (SPEx) [5] categorizes existing product databases that provide information about the energy performance and other characteristics of individual product models as follows

- **Certification databases**, to collect national or regional information on compliant or non-compliant products on the market;
- **Product databases for modeling purposes**, enabling governments to connect sales and efficiency trends to help inform the development of future policies;
- **Consumer information databases**, to enable smart and informed purchasing decision-making by consumers, by using consumer mobile apps and online comparison tools.

SEAD [5] stresses, that “a number of product databases have been developed and are maintained by governments around the world, which are built either for internal governmental use or that are accessible to the public. These databases represent authoritative sources of information about the energy performance and other characteristics of individual product models commercially available in selected markets. These databases can be used for multiple purposes.”

In the EU, there are several different databases that compile differing amounts of data on general and energy-related product characteristics, such as:

- the Energy Star Product Database [6];
- Euro Top Ten [7];

- databases operated by industrial or consumer associations [8], energy agencies [9], research institutes [10] or environmental organisations.

The Energy Star Product Database could be characterized as a voluntary certification database because manufacturers have to register a product model to document its Energy Star compliance, whereby Energy Star is a voluntary energy efficiency label. The other mentioned examples are to be categorized as classical consumer information databases; their data is primarily based on surveys and targets part of the market, i.e. they gather only the data of most efficient products.

A prominent example of an obligatory certification database which is populated by the manufacturers / suppliers themselves is the US Compliance Certification Database [11]. This database facilitates and improves market surveillance in the US, and is also used to further develop and adapt US minimum efficiency performance standards. The fact that this database contains data on about 1.5 million products clearly suggests that even such a large number is no obstacle for setting up and operating such a database by self-registration.

The efforts for keeping a database, which is based on surveys, permanently up to date are very high and the continuity is not guaranteed since the funding for database development and data administration depends on time-limited projects. In the framework of the IEE (Intelligent Energy Europe) programme and its predecessors, several attempts have been made to set up a product database, e.g. HomeSpeed [12] and recently the Energy-related products database. The main reason why these projects did not succeed or were discontinued is the lack of structural and continued data input. Collecting the data once was not a problem, keeping the database up to date was. Furthermore, none of these projects aimed at a complete overview of the market for all products that have an energy label or ecodesign requirements. Hence, no current database in the EU provides on a continuous basis a complete overview of the labelling information and the ecodesign requirements of all product models available on the EU market that are covered by the Labelling and Ecodesign Directive.

An EU product database with the obligation for manufacturers to register labelling and ecodesign product data is the only way to achieve a complete overview of the market for the above mentioned stakeholders. This database should combine aspects of all three categories of databases mentioned above:

1. In order to gather all data the registration of model data should be mandatory similar to the certification databases, but this registration neither wouldn´t have the mandate nor the purpose to certificate compliance with Labelling and / or Ecodesign Directive as condition for market access of a product model, but to make information related to the labelling and ecodesign requirements of each product model available and comparable.

2. One of the main purposes of the database is to enable the European Commission to help to inform the development of future policies similar to the category “product database for modeling purposes”. Therefore it should include all data categories of this database except the sales data, because it would not be its purpose to connect sales and efficiency trends.

3. The database should provide the labeling and ecodesign data entirely to deliver a robust raw data basis to give stakeholders the opportunity to present information in an attractive way, e.g. for consumer information services to enable smart and informed purchasing decision-making by consumers, by using consumer mobile apps and online comparison tools, but it should not target consumer information directly. However, the data should be public available on internet to ensure a level playing field for all stakeholders.

Proposal for an EU product database

In this section we describe our proposal for an EU products database that will make the key product data required under the Energy Labelling Directive and the Ecodesign Directive publicly available.

Key points concerning the implementation, structure and operation of a feasible EU product database

1. Introduction of the database

The revision of the Labelling Directive will provide an opportunity for the creation of a products database containing the information printed on the label and regarding eco-design. Suppliers[1] should be obligated by the revised Labelling Directive to enter the data printed on the label, the label itself, the data on the fiche required under the Energy Labelling Directive and – if possible the key product data[2] required under the Ecodesign Directive and the relevant provisions implementing this Directive . This is the only way in which an overview of the market can be obtained.

Further it should be made compulsory for information on products that so far have been covered solely by the provisions implementing the Ecodesign Directive to be entered into the database. This applies to both to products covered exclusively by the Ecodesign Directive and to products which also fall under the Labelling Directive. However, no additional data categories such as sales, regional product availability, pricing, should be gathered in the database to minimize potential restrictions for the introduction of the database. Particularly requirements for this kind of data could cause obstacles, because of restrictions on data availability and data protection are to be expected. The data will be made available in a language-neutral way like on the label.

The database will merely be used to compile the data and make it accessible, whereas processing the data and presenting information will be left to third parties. The database will be operated by the European Commission or an agency designated by the European Commission.

2. Funding, purposes, target groups and operation of the database

The European Commission will finance the database and either the Commission itself or an agency designated by the Commission will be responsible for its concept design and for creating, maintaining and permanently operating the database in an orderly fashion. Main target group for the database will be the European Commission. By long-term funding and operating the database on a permanent basis, the European Commission will gain reliable, complete and robust data

a) to be able to develop and adapt requirements for labelling and ecodesign (target group: European Commission, consultants, researchers)

b) to provide the required electronic dataset to prepare the EU energy label, in particular for online trading purposes, but also to restore lost labels (target group: suppliers and retailers)

c) to make a major and cost-efficient contribution to support market surveillance throughout the EU, supplementing, but not substituting existing web-based instruments (ICSMS, Rapex) designed to support market surveillance (target group: market surveillance authorities)

d) the database would provide a publicly available, reliable and complete set of energy and consumer relevant information for consumers and other interested parties (target groups: end-users, consumer associations, environment organisations, researchers and other stakeholders). Thereby the database would create a new quality of transparency supplementing the conventional paper based energy labelling by digital labelling (and ecodesign) data.

Up to now, this data basis is created by project-based manufacturer queries, e.g. within the scope of the ecodesign preparatory studies. The effort that needs to be done for both the European Commission and the manufacturers may be omitted by the proposed database. The costs of implementation, data entry and operation of the database are thus partly compensated. At the same

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[1] suppliers within the meaning of Article 2 of Directive 2010/30/EU ("manufacturer or its authorised representative in the Union or the importer who places or puts into service the product on the Union market.") or by manufacturers within the meaning of Article 2 of Directive 2009/125/EC; hereinafter both groups will be referred to as "suppliers"

[2] The decision as to what data required under the provisions implementing the Ecodesign Directive must be included in the database is to be taken following close scrutiny of the respective provisions.

time, a significant qualitative and quantitative improvement in the data base by the introduction of the database is expected. However, a cost-benefit analysis should be carried out in order to quantify the EU-wide macroeconomic cost saving effects of the database compared to the status quo.

3. Data entry

The database would be filled exclusively by suppliers. Suppliers would be responsible for the correctness and topicality of the data in the database similar to the principle of self-declaration of energy label. To enter the data would require prior registration as a supplier. The Commission or an agency designated by the Commission would be responsible for verifying the suppliers registration data and for activating user accounts for data entry after a plausibility check.

The database would merely be used to store and provide the raw data. The data should be made accessible for use by third parties (including market-surveillance authorities, service-providers, energy agencies, consumer and environmental associations, scientific institutions, educational institutions etc.) via a data interface. The data should be processable and the results of this processing can be presented by any third party in any form (internet, paper etc) and even in various other contexts. This also means that every third party is liable for their presentation.

The database should also be designed in a way that allows suppliers to provide optional test certificates and reports which are sometimes requested by market-surveillance authorities. This would possibly further reduce the effort required to conduct market surveillance – both for suppliers and for the authorities, thus raising acceptance levels for online data capture among suppliers.

The database should have a straightforward structure and be easy to use. The data stored in the database should be universally accessible as it has to be published anyway – thereby no areas with limited access are needed. The suppliers' registration and authentication data and the log of their update history should only be accessible to the operator of the database and the market-surveillance authorities. In principle, the data regarding each model should be entered only once, notwithstanding any corrections and additions that need to be made.

4. Transition period

There should be a transition period during which the data regarding models that were placed on the market before the creation of the database and which are covered by one or both of the directives and the provisions implementing these, must be entered into the database.

5. Topicality of the data

It is important to specify whether models are still produced or placed on the market, so that the data available can be analysed and evaluated accordingly. Simply filing the date on which the model was first placed on the market would not suffice, as it can lead to erroneous information being logged – particularly where products with a short life-cycle are concerned. It would make more sense to include the categories of "still produced / placed on the market" and "no longer produced / placed on the market". The supplier could then indicate that their product or a certain model is no longer produced or placed on the market once they have taken the product off the market. The information about the product or model in question should, however, not be deleted from the database: first of all, because the model might still be available on the market '(e.g. second hand), and secondly because this data makes it possible to find out about developments in the product range.

6. Model identification

It is essential, not only for model data registration, but above all for market surveillance that the directive sets out the requirement for unambiguous identification of the model to be provided. This is the only way to ensure that product data on specific models can be retrieved from the database. Each product should be marked with a model identification code, allowing for the identification of every specific model for every supplier. Current regulations already require the manufacturer to provide in the technical documentation a list of equivalent models, i.e. a list of model identification codes that relate to models that have the same relevant technical characteristics, but could differ with regard to colour, plug or country where the product is sold.

Advantages for various stakeholders concerned

European Commission

- The use of a database makes it possible to see whether there is a need to review the requirements for energy-consumption labelling or for eco-friendly design applying to a certain group of products, without the need to clarify this by means of a study. Once it has been found that there is indeed a need for review and for a study, the database will provide further valuable information. This will save both time and money.

Market surveillance

- Market surveillance will become considerably faster and less complicated as the database will provide instant access to the key product information printed on the label and the data sheet. However, this assumes that every supplier enters the data of all models, which has to be surveilled accordingly.
- The database will also allow each and every model to be traced back to its supplier and the person / company responsible. This will eliminate the need for researching these, which so far has often been quite a time-consuming task. The product selection and strategy of market surveillance authorities would be made easier by the database and thus, effectiveness of market surveillance could be improved.

Consumers

- Though the data should be publicly available on the internet, consumers are not regarded as the primary target group of the online database. The data should be prepared by consumer organisations, energy agencies, retailers etc. to provide adequate consumer information, e.g. considering the local availability of the presented product models. These players will benefit as the database will deliver a reliable, permanent and free data source and hence, establish a level playing field.
- The database will offer myriad possibilities when it comes to additional applications that are extremely useful for the consumer, such as the possibility to search for the best product / model in a given category, calculate the cost of a product / model across its entire lifecycle, and / or in some cases, learn about the energy consumption of a specific product / model.
- Consumers will benefit from a full and up-to-date overview of the products that are on the market at a given time, which will make it easier for them to compare product information before choosing a certain product.

Suppliers

- Suppliers will be able to use the central EU products database to submit the online label they are required to provide.
- Given that consumers rarely ask to see the data sheet (fiche) of a model[3], it would be conceivable to consider dropping the existing requirement for a printed version of the data sheet to be provided if the data in question is instead made available via the online database.
- Suppliers will be spared a great deal of effort once they can simply point to the EU products database whenever they are contacted about the data in question.

Furthermore, the EU products database will deliver better market transparency, allowing suppliers to showcase their energy-efficient products more successfully.

Conclusions

Up to now, there is no possibility to check or to compare energy and further consumer relevant labelling and ecodesign information and requirements of all models of regulated product groups in the EU market. Gaining an overview of all regulated product groups in terms of their characteristics depicted at the EU Energy Label as well as their Ecodesign requirements would be of interest

[3] According to some authorities tasked with market surveillance.

primarily to the European Commission. The Commission needs a reliable, complete and robust data basis in order to be able to develop and adapt requirements for labelling and ecodesign for product groups subject to such requirements. No additional data categories such as sales, regional product availability, pricing, should be gathered in that database, because it would not be its purpose to connect sales and efficiency trends. Furthermore, a potential obstacle for the introduction of the database is thereby removed.
Existing product databases at national and EU level do not meet this task. An EU product database for which entry of labelling and ecodesign product data is mandatory is the only way to achieve a complete overview of the market. Therefore, this paper provides a proposal for a feasible EU product database which would be as simple and effective as possible to implement and to operate.

The European Commission should finance the database with a long-term perspective and either the Commission itself or an agency designated by the Commission would be responsible for its concept design and for creating, maintaining and permanently operating the database. The database should have a straightforward structure and be easy to use. The database will be populated exclusively by manufacturers and suppliers. It would merely be used to store and provide the raw data. The data would be made accessible for use by stakeholders and furthermore by third parties who could develop different information and service offers based on this consistent data and hence, a wide range of stakeholders could benefit from it.

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Assessment of Compliance Scheme of China Energy Labeling Program[1]

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Abstract

In 2013, a research funded by Asian Development Bank (ADB) was conducted to assess the compliance scheme of China Energy Labeling (CEL) program. This paper presents the results of the comprehensive assessment from the perspective of the legal basis and institutions, enforcement and penalties, financial and human resources, technical capacity, information sharing and public communication of CEL program.

According to the assessment, it is recognized that the framework of compliance regime of CEL program has been put into place after 10 years development. The following challenges and barriers were identified in the assessment: legal basis lf CEL is outdated and does not reflect rapid changes in the market and technologies. The legal foundation also lacks specific guidance and requirements for monitoring, verification and enforcement. Divided responsibilities between multiple agencies make it hard to coordinate MV&E activities. Local governments' efforts regarding market surveillance have been limited due to budget constraints, more attention on safety and lack of practical guidance. Very low penalties for non-compliance are also identified as a key barrier for compliance regime. CEL program lacks a consistent national designated budget from the state. Severe budget constraints have resulted in limited public awareness, absence of consistent market surveillance activities and uneven local enforcement. CEL program faces a much larger volume of registered test labs and limited resources which resulting in insufficient capacity building, inspections and round robin testing for testing labs. CEL program lacks a unified information collection and sharing system for different agencies. Consumers' awareness of compliance is low for absence of strategic public communication plan.

Based on the international best practices and gap analysis of the CEL program, the policy recommendations are also made for improving the compliance regime of CEL program.

Introduction

China is experiencing explosive economic growth and rapidly rising living standards. China's Law on Energy Conservation thus set an overall framework and strategy for tackling increasing energy consumption and severe environmental problems. Within this context, improving the energy efficiency of end-use products is a critical component. In response to that, China has developed the China Energy Labelling Program which is a kind of mandatory labeling program. The label templates for CEL program are shown in Figure 1.

[1] Project 2012BAK30B04 supported by National Key Technology R&D Program.

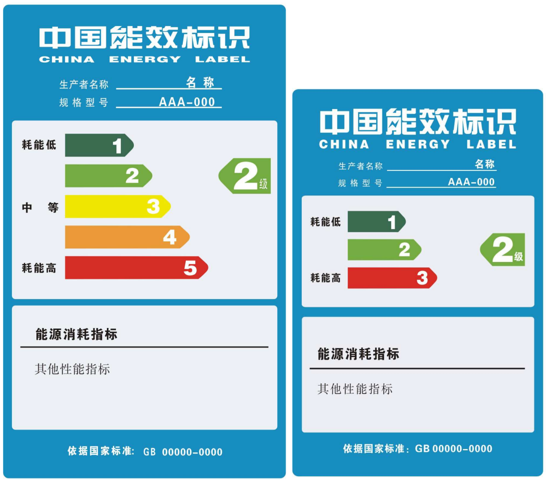

Figure 1 Label Template for China Energy Label

The CEL program was jointly introduced by NDRC, AQSIQ and Certification and Accreditation Administration of China (hereafter abbreviated as CNCA) in 2005 with air conditioner and refrigerator released as the first batch of target products. China National Institute of Standardization (CNIS) was authorized as the implementing agency jointly by AQSIQ and NDRC. The CEL helps consumers easily identify energy-efficient products and in doing so, helps stimulate the purchase of highly energy-efficient products. It is an information label and displays the energy efficiency grade, main energy consuming parameters, manufacturer name, product model, and reference standard on which the label is based. The CEL is now required for a total of 29 products including 15 household appliances, 5 industry equipment, 3 office equipment, 4 commercial equipment, and 2 lighting products. Label registration in China Energy Label Center (CELC, directly under CNIS) is required for all manufacturers and products, and manufacturers need to fill and submit the application materials including basic situation of manufacturers, label sample, energy efficiency testing report through the website. After the application is reviewed, approved and announced to the public on the label website by CELC, manufacturers are authorized for nation-wide label usage.

In 2013, a research funded by Asian Development Bank (ADB) was conducted to assess the compliance scheme of China Energy Labeling (CEL) program. This paper presents the results of the comprehensive assessment from the perspective of the legal basis and institutions, enforcement and penalties, financial and human resources, technical capacity, information sharing and public communication of CEL program.

Methodology of assessment

For the analytical framework, the main areas of the assessment include: label registration process for products, implementation of supporting policies, supervision of testing laboratories, market surveillance and label compliance trends.

Compliance scheme of some successful cases, including US, Australia, EU and Japan, were selected to be compared with CEL. The key topics for the case studies of successful international labeling schemes include: legal basis, implementation scheme, resources, technical specifications and capacity building of the evaluation system of international energy labeling programs.

The recommendations from this study focus on both regulatory and technical aspects to improving CEL compliance. In addition, the project analyzed policy and technical barriers to compliance in the CEL evaluation system as the basis for making recommendations.

Policy and Technical Barriers to Compliance in the CEL

Although the CEL achieved remarkable results over a short period of time, there are still problems that could affect CEL's effectiveness and overall policy impact. Since CEL information is self-declared by manufacturers, they tend to overstate it. Due to unclear institutional roles and responsibilities, incomplete supervision system and measures, weak local label enforcement efforts, insufficient resources input, inadequate technical capacity and information communication, label compliance evaluation and supervision work are not fully performed. The main barriers that exist in label compliance evaluation and supervision system are discussed below.

Legal basis and institutions

CEL is created out of state proposals and the mandatory program has a strong legal basis in national laws as well as other countries. Regulations of China Energy Labeling Program (RCEL) and Energy Conservation Law (ECL) have together established a strong legal basis for CEL. There are no major barriers in the legal framework. However, after near nine years' implementation, the market situation and policy environment have changed a lot. RCEL needs to be revised to further clarify label surveillance methods, improve definitions of violations and make stricter penalties and follow-up rectification requirements in alignment with ECL which has stricter penalties for manufacturers.

For institutional roles and responsibilities, China also has clear definitions among governing departments and implementing agencies as well as other countries. China's Energy Conservation Law and other supporting laws and regulations outline the division of responsibilities for enforcing and supervising implementation of the label between three departments of the AQSIQ at the national level and local quality supervision, inspection and quarantine departments at the local level as listed in table 1. This is very different from other countries where a single energy regulator, either at the national or sub-national level, is typically tasked with label implementation and enforcement.

Table 1 Roles and Responsibilities Regarding Market Surveillance in the PRC

Level	**Domestic Market**		**Import/Export**
	Manufacturers Factories	**Retailers**	
National Level	AQSIQ	SAIC	AQSIQ
Local Level	Local quality supervision and inspection bureaus	Local industry & commerce administration bureaus	Local entry-exit inspection and quarantine bureaus

The resulting challenges that may exist include the following aspects:

- Functions within certain label supervision departments are overlapped or ambiguous. On the local level, the label governing department may be not clearly defined which usually leads to poor implementation and may cause problems such as mutual evasion of responsibilities and negligence by all parties.
- The separate supervision responsibilities over the manufacturers and market by local Administration of Quality and Technology Supervision (AQTS) and Administration of Industrial & Commercial (AIC) may easily result in supervision loopholes or dead zones, impairing effects of supervision.
- Insufficient cooperation, coordination and integration of supervision resources at various levels and among different regions may result in unsatisfactory supervision effect.

Label technical specification and development

A key success factor identified amongst international programs is that they all conduct comprehensive market and technological analysis to determine labeling thresholds and then hold public comments and review periods to ensure the proposed labeling requirements are set at appropriate levels.

China's development process of label specifications is very similar to Australia[1] and Japan[2], and is closely linked to its energy efficiency standards which contain both MEPS and energy grades. However, China does not currently follow a specific set of guiding principles for deciding which new products to add to the CEL program. In setting the MEPS level and labeling thresholds, China has established a complete work procedure and technical analysis system. However, due to tight budget, limit on data availability, modeling analysis capabilities, China cannot always incorporate as much detail and complexities into its technical analyses as developed countries have such as in the engineering analysis, energy and water use analysis, mark-up analysis, life-cycle cost and payback analysis, market and shipment analysis, national impacts analysis, manufacturer impact analysis, life-cycle cost analysis, employment impact analysis, utility impact analysis, regulatory impact analysis, and environmental assessment done in the USA. China is especially poor in manufacturer, employment and environment impact analysis.

Implementation schemes

The implementation process for China's Energy Label is very similar to that of the USA and Australia, consisting of manufacturer self-reporting and self-certification of energy efficiency test results that demonstrate the labeling requirements have been met. In addition to the manufacturer self-certification during the initial label registration process, China has established a certification process for testing labs as early as 2009 which is earlier than many countries and set a good example. However, unlike the ENERGY STAR program[3], CNIS does not conduct ongoing verification testing so labeling implementation is primarily done through the initial one-time product testing for the label registration. This is due to severe budget constraints and lack of motivation and capacity at the local government institutions responsible for conducting market surveillance. In fact, the lack of consistent label display compliance surveys and local verification check-testing are the two key weaknesses in China's label implementation process. Without either regular label display compliance surveys such as those conducted in some EU countries or ongoing verification testing[4], there is greater need for strong enforcement mechanisms and deterrence (discussed below) to ensure that compliance is being met after the product has been registered and is distributed on the Chinese market. From 2010-2012, CNIS organized pilot label display compliance survey and check-testing in Shanghai, Sichuan, Shandong, Guangdong, and Jiangsu provinces funded by Energy Foundation. The results of display compliance survey was shown in Fig. 2.

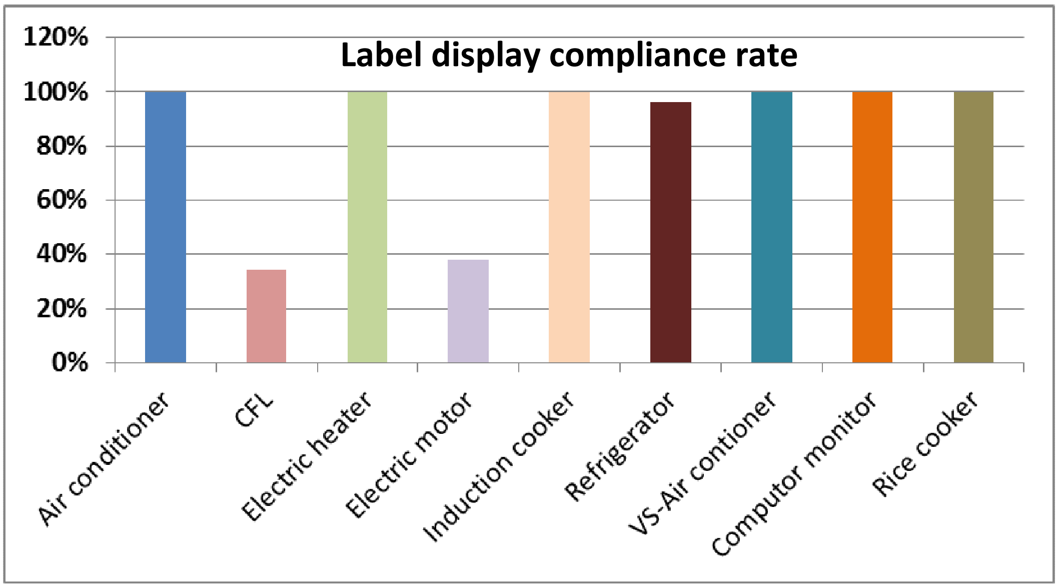

Figure 2 Label Display Compliance Rate

In terms of raising labeling awareness, although CNIS has started to conduct retail promotional activities to promote consumer awareness and trainings with manufacturers, most of these activities are relatively ad hoc and there is not a systematic framework or strategy for communications yet.

Enforcement and penalties

Unlike all other countries and labeling programs where implementation and enforcement falls generally under the energy regulatory agency responsible for managing the labeling program, China's national implementation and enforcement responsibilities is designated by law to administrative departments responsible for overall product quality supervision and management. This is a major challenge because there are other product quality priorities for these departments, such as consumer product safety, which often overshadow energy efficiency in the national random product inspections that are conducted regularly. Given the department's limited resources for enforcement and priorities on consumer product safety, there have not been any consistent national product inspections or testing focused on compliance with the China Energy Label's energy efficiency requirements. Because the enforcement and monitoring responsibilities are also split between the quality supervision department, and industrial and commercial product departments, coordination in conducting inspections and enforcement efforts is also much more difficult and a major barrier to effective enforcement.

At the local level, a major barrier is that local quality supervision inspection and quarantine departments lack the financial and technical resources to conduct consistent enforcement of the China Energy Label over time. There is no large-scale check-testing at the sub-national level and only a few regions with some technical capacity for product energy efficiency testing have been able to conduct pilot check-testing projects. These pilot check-testing projects, as well as previous national check-testing efforts, have not incorporated risk-based product selection that targets manufacturers more likely to be non-compliant, which has been utilized in Australia[5] to more effectively verify compliance with limited resources. The results from the most recent pilot check-testing in 2010-2011 showed large variations in check-testing results by product and region, suggesting that there are weaknesses in both technical capacities for testing and actual compliance levels across regions. Another related barrier is that because China has many more manufacturers than other countries, it will need more resources and budget to ensure compliance than countries.

Compared to countries like Australia, EU and Japan where testing laboratory certification is not required for their energy label registration, China's process and requirements for testing laboratory registration, spot inspections and even round-robin testing are much more rigorous. This laboratory management system help ensure that the energy performance data reported in the label registration is accurate and provides a sound technical basis for implementing the Energy Label requirements. However, as discussed further in the technical capacity section, there is still a wide variation in the technical capacities of different testing laboratories due to the sheer volume of registered test laboratories in China and different resource and capacity levels. Moreover, while rigorous laboratory certification and management are important in establishing compliance from the beginning of the labeling process, it cannot replace the market surveillance efforts that are needed to ensure that all product models meet performance and labeling display requirements after they have been certified in the initial label registration process and are in the market distribution phase.

In addition, the penalties for label violations are not heavy enough to curb label fraud. As defined in RCEL and ECL, the maximum penalty for forging or illegal use of energy label is only 100,000 RMB (16,000 USD) and severe violator may be subject to business license suspension by industrial and commercial administrations, which doesn't put any strong deterrence to unlawful acts. Moreover, there is inconsistency between the intensity of punishment in these two regulations, possibly leading to confusion. Therefore, insufficient penalties are another key barrier for CEL enforcement.

Financial and Human Resources

A major challenge in the China Energy Label program is the chronic shortage of sufficient and consistent financial and human resources to support label development, implementation and enforcement. CEL receives the lowest fund from the national government. Currently, all of CEL related expenditures are co-financed by CNIS at a level of less than 5 million RMB per year, and very limited budget are allocated by local government for label monitoring and surveillance. China also does not have any fixed or consistent funding for its energy label program and most of current funding is provided from CNIS's overall budget or through research and international grants and funding. This unstable and insufficient financial resource for S&L programs has resulted in limited public awareness of the labeling program, absence of consistent national check-testing and retailer survey programs, and uneven local enforcement of the labeling program. More specifically, most provinces and cities have not planned and arranged supervision and inspection of the CEL and there are often no fixed institutional arrangements, law enforcement procedures and special technical documents to support CEL enforcement. Personnel allocation also fails to meet requirements of label supervision and inspection, and supervision coverage is quite limited. In addition, as a new task, energy label supervision requires law enforcement personnel to be familiar with relevant label registration and implementation procedures and their requirements as well as network platform. Shortage of working funds leads to shortage of local human resources or lack of qualified and fully trained law enforcement personnel. This is the main barrier to effective CEL enforcement.

Thus, the management, guidance and support for the relevant government agencies responsible for implementing the energy efficiency standards and labeling programs in China are insufficient. Moreover, China also lacks a designated budget for monitoring and enforcement at both the national and local level. Lastly, the China Energy Labeling program relies entirely on centralized funding and support from the central government as local governments have not provided any financial or complementary support to label implementation and enforcement.

Information sharing

China has information sharing practices in its enforcement of the China Energy Label program, but lacks a framework or centralized platform for sharing compliance information with the public that is common in international labeling programs. In China, a product's label registration information, including its claimed energy performance, is reported to the public on the China Energy Label website but information about products that fail to meet labeling requirements are published on the Quality Inspection department website.

China also has varied compliance information disclosure and issue system depending on local quality supervision bureaus. At present, there is no reporting system for label supervision and compliance evaluation results and no specific personnel in charge of data collection, tracing and handling. China also lacks a platform and channel for the unified publishing and issuing of label supervision and compliance evaluation information among AQSIQ, local quality supervision departments at all levels and China Energy Label Center. Moreover, some quality supervision departments impose differentiated treatment regarding information disclosure for local products and non-local products in order to exercise local protectionism. Check-testing results are also not often made publicly available, making it difficult for consumers to access information about products that have been verified to be compliant. China also has not demonstrated any instances of systematic information sharing across institutions and stakeholders. In addition, due to the absence of an information communication system, the linkage between label supervision and label registration has not been realized, resulting in limited regulation over manufacturers. Thus, the lack of systematic information sharing platform is another key barrier for the CEL.

Program evaluation activities

China currently has limited capacity and resources to conduct program evaluations in support of the China Energy Label program. In the CEL program's initial years, there has not been any systematic evaluation of the label program due to insufficient personnel and funds, insufficient energy efficiency and market data for only a few years due to limited data collection channels, lacking of assessment experience, and inadequate modeling and analysis capacities. Without more consistent program evaluations such as labeling awareness surveys, it is difficult to assess the overall level of labeling awareness amongst manufacturers, retailers and consumers or know where the greatest areas in need of improvement are in implementing the label. Moreover, China also misses out on important information about compliance levels that could be identified by program evaluations that highlight a gap between projected labeling impacts and the actual market transformation impacts and savings achieved. For example, program evaluations that reveal much lower market transformation and energy savings from an implemented label help clearly highlight implementation problems and compliance shortfalls that are hampering the projected savings from being achieved.

At present, the energy label system is entering a critical stage where further improvement of all implementation linkages, systematic review and scientific program evaluation are required so as to identify and address remaining weaknesses in the program. Similar to Australia [6], China has just carried out a rough one-time evaluation of CEL energy saving impact. This a big gap compared to the US ENERGY STAR program, which has conducted more consistent impact evaluations. Thus, inadequate program evaluation efforts and capabilities are also big barriers for CEL improvement.

Conclusions

To improve the legal basis for the energy labeling program, the current laws, particularly the RCEL, need to be revised and updated or a new comprehensive law or policy focused only on the energy labeling program needs to be introduced. The revised legal framework also needs to strengthen enforcement mechanisms by: improving definitions of violations, increasing maximum fines, setting stricter penalties and, and follow up on rectification requirements in alignment with the ECL.

In addition, current regulations can also be improved to provide a stronger legal basis for improving the quality and capabilities of testing laboratories. This could be done by requiring national round-robin testing, and specifying fines and penalties (including revocation of laboratory registration) for testing laboratories that provide false or inaccurate testing reports. Rather than relying primarily on the examination of written application documents to screen laboratory performance, there needs to be greater emphasis on using on-site inspections and round-robin testing to verify actual laboratory testing capabilities and performance. To maximize the limited resources for both of these activities, the selection of laboratories for inspections and round-robin testing can be targeted towards smaller laboratories and laboratories in less developed regions where weak capacities have been observed more often. China can also tap into its existing national laboratory accreditation process to prevent duplicative efforts in screening energy efficiency testing laboratories that have already been accredited and are already subject to other capacity and performance verification activities by the accreditation body.

A consistent national level check-testing program is urgently needed in China given the lack of focus on energy efficiency testing in current national product quality inspections. In order to maximize limited resources, the national check-testing program should consider following the targeted sampling approach that has become increasingly popular in international labeling programs. Developing product sampling criteria that targets specific products, manufacturers and regions that are more likely to have high non-compliance can more effectively identify non-compliant products and highlight the risks of non-compliance with smaller budgets.

A more structured framework is needed to improve coordination and provide clearer division of responsibilities between the relevant departments, the local quality supervisory departments and the CELC. A method would be to develop a centralized platform for information sharing that includes information sharing between the different regulatory agencies. At the local level, more training and capacity building are needed in order to raise the awareness and enforcement capabilities of local product quality supervisory departments, particularly in less developed regions where non-compliance has been a greater challenge.

Another recommendation for improving the China Energy Label implementation is to develop comprehensive recognition and marketing programs for promoting the label. Developing a comprehensive manufacturer and retailer recognition program can provide many benefits to implementation of the China Energy Label, including helping garner industry support for the labeling program, encouraging both manufacturers and retailers to comply with labeling requirements and strive for manufacturing and selling higher efficiency products, and helping shift some of the label marketing and promotional efforts from the CELC to retailers.

In addition to improving market surveillance activities, China should also expand its use of punitive measures to bolster the enforcement of the China Energy Label program. Informal punitive measures such as “naming and shaming” and publicizing all instances of non-compliance should also be used more frequently to support market surveillance activities.

As shown by the inadequacies in financial and human resources currently supporting China’s energy labeling program, significant increases are needed in the program budgets for both label development and management, and implementation and enforcement. Stable fund from state revenue for CEL is urgently needed and is of key importance to CEL’s smooth development. This budget can also be used to support the improvements that are needed in the label implementation and enforcement as discussed in previous sections. In addition to the national budget, financial resources also need to be allocated to local quality supervisory departments to support local enforcement and check-testing.

A centralized platform can also be used to help facilitate communication and information sharing with external parties such as manufacturers, testing laboratories, retailers, consumers and other stakeholders. There also needs to be greater policy emphasis through policy directives or formal meetings and workshops for instance, on promoting both formal and informal collaboration and information sharing between the different market surveillance institutions and enforcement efforts.

Conducting program evaluations can provide important feedback on the China Energy Label program and will require more resources to support regular labeling awareness surveys to identify gaps in public awareness and acceptance. Retrospective program evaluations using collected data about changing market shares for products with different labeled efficiency grades should be conducted to provide more information on the labeling program's effectiveness in promoting market transformation and help quantify its actual energy savings impacts. In the longer term, it may also be considered to use qualified third-party evaluators to conduct regular program impact evaluations and process evaluations.

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Achieving Effective Compliance through Regional Coordination: Transferring the Lessons Learned in Europe to the APEC region

Abstract

Ensuring compliance – the process of monitoring, verification, and enforcement (MV&E) of energy efficiency standards and labelling (S&L) – is fundamental towards achieving expected energy savings from appliance energy efficiency policies. Globally, non-compliance remains a major challenge. It is estimated that up to 25% of potential energy savings in mandatory S&L programmes are lost through poor compliance and enforcement.

Compliance testing, which verifies the energy performance claim of a product, is a critical, yet resource-intensive element of an MV&E framework. Particularly, the high costs of compliance testing have been identified as a common barrier for economies in the Asia-Pacific Economic Cooperation (APEC). Considering there are many common products traded within the region, a coordinated approach on regional compliance schemes can reduce costs of testing for individual economies and, at the same time, increase developing economies' access to compliance intelligence information, and enhance the compliance activities and capacity of the APEC region.

The European Union has faced similar challenges undertaking verification tests, mainly due to the high costs of testing and the lack of accredited laboratory facilities. To maximize testing resources, the EU is undertaking initiatives to coordinate Member States' market surveillance programmes by increasing communications, information-sharing on technical documents, product information, and test data among EU Market Surveillance Authorities (MSAs).

The paper will discuss a potential coordination effort being formed in the Asia-Pacific region. Using the EU as a case study, the paper will identify how the lessons learned in Europe can be built upon or replicated in the APEC region for a cost-effective regional compliance scheme.

Introduction & Background

The residential sector accounts for over 14% of the world's total energy consumption.[1] With population growth and urbanization driving an expected increase in the ownership of household appliances around the world, energy efficiency standards and labelling (S&L) policies for lighting and appliances offer proved and substantiated potential for energy and carbon emissions reductions, consumer savings, and cost-effective energy conservation policies.

Compliance – or monitoring, verification, and enforcement (MV&E) – of these high-impact policies is an essential and critical aspect of an S&L programme. *Monitoring*, commonly referred to as *market surveillance* in the European context, involves checking products on the market to ensure that programme requirements are complied with. *Verification* confirms whether a product lives up to its declared energy performance claims in accordance with S&L policies – often by testing a product against a specified test procedure, via either a third party laboratory or in-house testing facility. *Enforcement* policies outline a set of rules or actions to be carried out by regulators when incidents of non-compliance have been identified and investigated,

A robust MV&E framework brings various benefits to all stakeholders involved in the MV&E framework. For governments, compliance ensures that products perform as claimed by manufacturers and importers, thereby safeguarding the expected energy and greenhouse gas savings anticipated from S&L regulations. For industries, it means those that invest in more efficient products have their investment protected and are not undercut by cheaper, non-compliant products. And finally, consumers purchasing high energy efficient products receive the performance they expect and pay for.

[1] IEA International Energy Outlook (2011)

However, globally, non-compliance contributes to losses in CO_2 emission savings of 112 Mt per year. Further, it is estimated that up to 25% of potential energy savings in mandatory S&L programmes are lost through poor compliance and lack of enforcement of these policies.[2] Limited human, financial, and information resources often create barriers and impede implementation of robust MV&E programmes. For instance, testing products for compliance is a critical element of the verification process but can involve significant costs – conducting a full verification test on one air conditioner model at a laboratory can cost more than $1,500[3] Due to these high costs, many countries, particularly developing countries in the APEC region, have identified verification testing as one of the major barriers to implementing more robust verification activities.

Member States of the European Union (EU) and the European Economic Area (EEA) have faced similar challenges with regards to verification testing, mainly due to the high costs involved and the lack of accredited laboratory facilities known to market surveillance authorities (MSAs). According to a survey carried out by CLASP in 2010, just over 50% of Member States reported that they have undertaken verification testing, although in some cases these tests were carried out by other organizations such as consumer organizations.[4] The EU Member States that participated in the survey identified three primary barriers for not undertaking more testing: high testing costs; a lack of laboratory facilities; and compliance of energy efficiency standards not being a priority issue for the government.[5]

Although implementing MV&E activities can be resource-intensive, there are opportunities to achieve higher rates of compliance more efficiently and cost-effectively. Particularly, in the Asia-Pacific region, many common high-impact appliances, such as lighting, televisions, refrigerators, and air-conditioners, are manufactured and traded within the region. This presents significant opportunities for MSAs in the 21 APEC member economies to use coordinated and creative approaches towards minimizing operation costs, such as verification testing costs, while improving compliance rates at the same time.

Working collaboratively achieves more than simple cost savings. Sharing market intelligence and expertise can also contribute to increasing human and information resources to implement MV&E activities. In Europe, for example, several MV&E initiatives are focused on coordinating Member States' efforts to facilitate communications and information-sharing on technical documents, product information, and test data. There are also multiple efforts led by some of the Member States to develop an effective and responsive network for market surveillance of the Ecodesign and Energy Labelling regulations. Leveraging the experiences from Europe, the economies in the APEC region are also developing a project to coordinate a similar regional effort - a voluntary mechanism focusing on MV&E information and best practices sharing. Both regional coordination initiatives in the EU and the APEC will be examined and analyzed in this paper.

Compliance Practices in the Asia-Pacific region

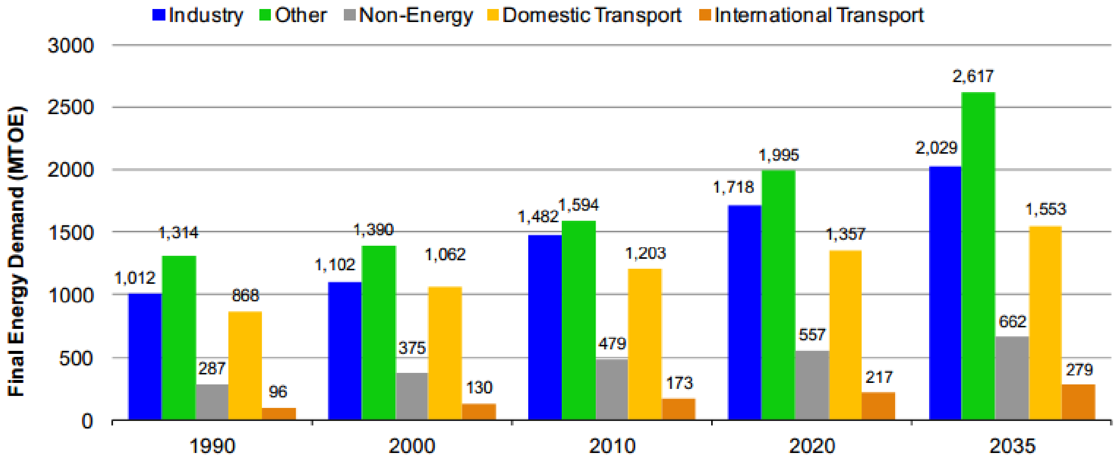
Big Picture: Energy Use in the APEC Region

Rapid growth in population, urbanization, and the average GDP per capita are driving an expected increase in the ownership of household appliances in several fast-growing APEC economies. The average GDP per capita in the APEC region will rise from USD 13,543 in 2010 to USD 33,233 by 2035.[6] As a result of the significant GDP growth, energy use in the APEC region is also predicted to increase as a result of consumers demanding more energy services. These services – such as a greater use of energy in more climate-controlled housing, in more home appliances, in more commercial services and within a larger industry – will result in a significant growth in energy demand. Energy use in the residential and commercial sectors in the APEC region is estimated to grow faster

[2] IEA Policy Pathway: Monitoring, Verification, and Enforcement (2010)
[3] CLASP, Assessment on Testing Capacity in the APEC region. 2014.
[4] CLASP, MV&E Survey, 2010. (ATLETE, 2010)
[5] CLASP, MV&E Survey, 2010.
[6] APEC Energy Demand and Supply Outlook – 5th Edition, APEC Energy Demand and Supply Overview

in comparison to other sectors – in terms of both energy use (from 1,893 Mtoe in 2010 to 2,450 Mtoe in 2,450) and percentage (64%). [7]

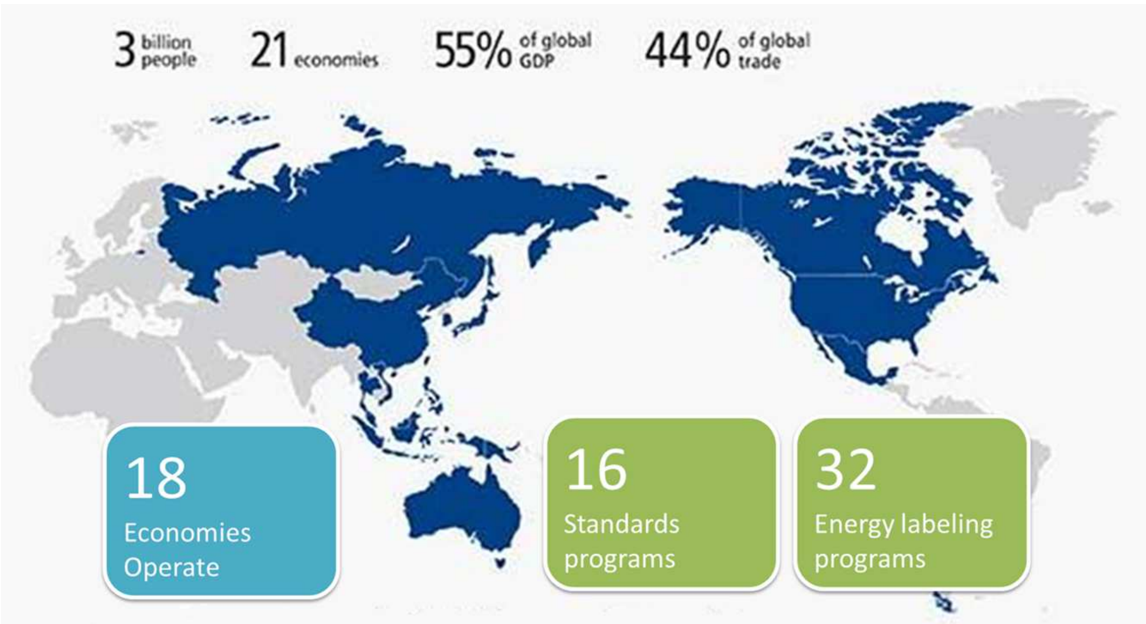
Figure 1: APEC Final Energy Demand by Sector



Source: APERC Analysis (2012)

Appliance energy efficiency policies offer proved and substantiated potential for energy and carbon emissions reductions, consumer savings, and cost-effective energy conservation policies. For this reason, most economies in the APEC region have adopted energy efficiency S&L programmes. There are a total of 32 energy labelling and 16 minimum energy efficiency standards programmes currently operated by 18 APEC member economies.[8]

Figure 2. S&L Programmes in the APEC Region



However, market characteristics among economies currently implementing S&L programmes vary significantly by economy. Some boast the world's largest manufacturers on the global market, while others rely solely or mostly on imported products. The maturity of S&L programmes in the APEC

[7] APEC Energy Demand and Supply Outlook – 5th Edition, APEC Energy Demand and Supply Overview
[8] CLASP S&L Database

region falls on a wide spectrum: from programmes that have been operating since 1978 to those that are just now starting to develop or implement their S&L programme; and from programmes covering more than 50 product categories to those that cover a single product. Due to the vast differences in S&L programme coverage and stringency, many APEC economies with more nascent energy efficiency policies have been targeted as a safe-haven for dumping non-compliant products.[9] For this reason, the 18 economies running S&L programmes have decided to take on the challenge to increase compliance of appliances and equipment on their market,

Regional Approach for Enhancing Compliance in the APEC Region

The APEC region is well placed to take a regional coordinated approach for enhancing and increasing compliance activities. The APEC market is vast and growing very rapidly. According to the World Bank's statistics in 2003, trade among members of the APEC accounted for about 57% of world GDP and about 47% of global trade.[10] The APEC region is becoming one of the largest commercial goods trading markets in the world. Additionally, many appliances and equipment, such as lighting and televisions, are manufactured or assembled in the region and supplied to markets around the globe. China, for instance, is one of the primary home bases for many appliance manufacturers and 60% of China's total foreign trade took place with other APEC economies.[11] Given the trade interdependency between APEC economies, there is considerable opportunity for the APEC region to work towards a seamless regional economy and to develop regional initiatives that could improve the transfer of knowledge and experiences amongst economies with respect to energy efficiency S&L programmes and their MV&E regimes.

Past Compliance Efforts Undertaken by the APEC Region

The APEC region has undertaken several efforts to facilitate dialogue and collaboration on MV&E between economies. In 2011, the APEC Expert Group on Energy Efficiency and Conservation (EGEE&C)[12] conducted a research project to compile information on MV&E processes used by regulatory and enforcement agencies to ensure compliance in S&L programmes within APEC economies. The research, "Survey of Market Compliance Mechanisms for Energy Efficiency Programs in the APEC Economies," has yielded eight recommendations to address the shortfalls in MV&E progress in the APEC region and assists the further development of a regional compliance culture. The recommendations include:

1. Raising awareness of compliance issues in all APEC member economies is critical to establishing and enhancing the operation of effective MV&E frameworks. Organizations such as APEC are critical to bringing compliance issues to the attention of APEC economies.
2. Governments need to plan and allocate sufficient resources for implementing robust MV&E processes, including provision of training for staff in charge of compliance activities.
3. Operational guidelines that outline the details of MV&E procedures should be made available to all stakeholders to minimize the misunderstanding of programme requirements or potential disputes.
4. Communications activities play a vital role in signalling the importance that governments place on compliance, making the risks of non-compliance obvious to stakeholders of S&L programmes.
5. Access to competent public or private testing facilities is a key barrier for most APEC economies. There are opportunities for APEC economies to initiate more cooperative and creative approaches to access testing resources on a regional basis.

[9] In 2003, at the 22nd APEC Expert Group on Energy Efficiency and Conservation (EGEE&C) meeting, APEC economies agreed to improve compliance with each member economy's regulations and avoid dumping of non-compliant products. http://www.egeec.apec.org/dmsdocument/229

[10] http://www-wds.worldbank.org/external/default/WDSContentServer/IW3P/IB/2003/04/11/000094946_03040104075221/Rendered/PDF/multi0page.pdf

[11] http://english.gov.cn/state_council/ministries/2014/11/04/content_281475005352737.htm

[12] The APEC Expert Group on Energy Efficiency and Conservation (EGEE&C) promotes energy conservation and the application of energy efficiency practices and technologies in the APEC region. It does this through advancing the application of demonstrated energy efficiency practices and technologies; contributing to international efforts to reduce the adverse impacts of energy production and consumption; and improving the analytical, technical, operational and policy capacity for energy efficiency and conservation within APEC economies.

6. Although costly, verification testing is a core feature of a successful compliance framework. There are benefits in adopting a more coordinated approach to testing which can include significant cost-savings from either more targeted or joint testing,, and valuable market intelligence that might not be collected by a single economy.
7. Industry's support is critical to the success of an MV&E framework. Governments should engage with industry participants – through regional forums such as APEC – to work together to develop more effective MV&E processes, whilst reducing regulatory burdens on industry.
8. The APEC economies could consider supporting a regional forum dedicated to MV&E, in order to improve compliance rates in the APEC region and to develop collaborative projects intended to share best practice, carry out joint testing, or share market intelligence.[13]

In June 2012, APEC member economies convened at the APEC Market Compliance Workshop in Beijing[14] to address the barriers and recommendations identified in the aforementioned research. The workshop enabled participants to work together to identify common barriers to improving compliance activities in the region and to recognize opportunities to work collectively on these issues. The barriers and opportunities identified at the workshop included the following:

- Compliance has taken a back-seat to other energy efficiency and conservation policies, so many MV&E authorities have not been given appropriate training and, therefore, lack the experience, knowledge and resources needed to apply appropriate solutions to improve national MV&E;
- Due to the diversity of S&L programmes and MV&E regimes amongst APEC economies, there is no "one size fits all" approach for achieving higher rates of compliance; and
- As appliance models are traded throughout the APEC region, there are opportunities for using cooperative and creative approaches among MV&E authorities to minimize the cost of testing (e.g. mutual recognition of test reports) and to increase the dissemination of test results.

Many APEC economy representatives expressed commitments to the policy recommendations emerging from the workshop. These commitments included:

- To make the risks of non-compliance obvious and accessible to stakeholders in S&L programmes, through increased communication activities and by raising the profile of MV&E activities and results;
- To use cooperative and creative approaches in order to minimize the cost of testing. For instance, two technically equivalent economies can adopt the mutual recognition of test reports;
- To engage with industry participants to develop effective MV&E approaches, such as industry certification schemes; and
- To develop a regional MV&E network, similar to the model applied in the European Union, under the umbrella of the APEC EGEE&C or other regional bodies.

Recent Efforts to Increase and Improve Regional Collaboration on Compliance

Building on commitments and consensus, in 2013, APEC economies started pushing forward the concept of creating a regional MV&E forum in the APEC, intended to facilitate continuous information sharing and partnership development and to identify and share best practices to overcoming common barriers, such as carrying out more verification testing with fewer resources.

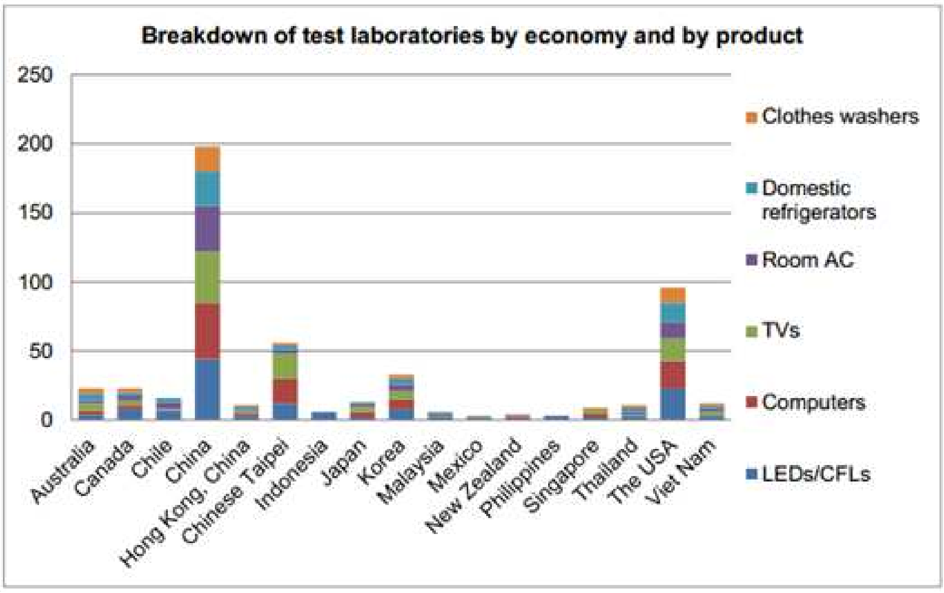
In collaboration with multiple economy partners and led by Australia and New Zealand, the APEC EGEE&C initiated a comprehensive assessment of testing capacity in the APEC region to identify gaps and develop recommendations for a cost-effective regional verification testing scheme for the region[15].

A range of surveys carried out as part of this assessment identified some 250 qualified testing laboratories across 17 APEC economies. In an unsurprising correlation between size of the market and available testing capacity, economies with the largest manufacturing capacities, China and the

[13] Mark Ellis, APEC MV&E Survey
[14] APEC Compliance Workshop 2012:
http://clasp.ngo/en/Resources/MVEResources/MVEPublicationLibrary/APEC-Compliance-Workshop.aspx
[15] Link to APEC Project on EGEE&C website

United States, were found to have the most testing facilities to accommodate the size of the market. In smaller economies, insufficient testing capacity exists to support all the national appliance energy efficiency policies. To compensate for insufficient testing capacity, the assessment recommends that smaller economies leverage test facilities from neighbouring economies. For example, due to Vietnam's constrained laboratory capacity to test domestic refrigerators, a laboratory in Thailand has been officially designated by the Vietnamese authorities to certify this product category.

Figure 3: Breakdown of Test Facilities in the APEC Region by Economy and by Product



Additionally, building a collaborative network of MV&E authorities could substantially support development of successful MV&E regimes in the APEC region. Such a network would provide the foundation for active and open communication channels and information exchanges that are key enablers for collaborative activities. There are, of course, costs associated with this type of activity, such as costs required for travel, and for building online sharing platforms or databases. These are, however, outweighed by the benefits such a network could bring, which include improved leverage, skill building, support for smaller economies and testing cost savings.[16]

By providing effective solutions to address those barriers currently faced by MV&E authorities in the APEC region, member economies can expand on existing regional collaboration and information sharing, thereby enhancing the technical capacity of APEC economies to develop effective MV&E policies and to overcome the common barriers to implementing successful S&L programmes.

Australia conducts lamp testing in China to reduce programme costs

An example of how the recommendations outlined above can be successfully adopted in practice can be seen from a case of successful collaboration between Australia and China. In 2010, the Australian Government commissioned the National Lighting Test Centre (NLTC) in Beijing, China, to undertake performance testing of CFLs available in the Australian market. Over 2,000 lamps were tested (140 individual models) against a range of performance criteria including light output, efficacy, color rendering, lumen maintenance and lifetime. Additionally, a proportion of the lamps were tested for mercury content.

The results of this testing are serving as a benchmark for measuring improvements in CFL quality following the implementation of performance and energy efficiency regulations implemented as part of the Australian Incandescent Lamp Phase-out actions.

[16] http://www.clasponline.org/en/Resources/MVEResources/MVEPublicationLibrary/APEC-Assessment-of-Testing-Capacity-Facilitates-Compliance-Collaboration.aspx

The competence of NLTC to undertake this compliance testing on behalf of the Australian Government had been established before 2010 through comparison testing with laboratories in the United States and Australia. Since the initial tests were carried out, the Australian Government has commissioned NLTC to undertake a range of testing activities including assessment of market developments (particularly for CFLs and LEDs) and the management of a round robin test verifying a new reflector lamp test methodology.[17]

EU's experiences and approach to enhance MV&E frameworks

Despite some significant differences with regards to its legal framework and single market, the EU offers an example of how multiple economies can work together at a regional level to improve compliance with product-focused legislation using minimal resources. The APEC region has therefore looked to the EU to better understand how regional collaboration can support compliance activities in individual economies, as well as how regional collaboration can be established, whilst gaining insight to common challenges and best practices for MV&E.

The EU operates as a single market, where goods, services and people are free to move across Member State borders. As a result, Member States are governed by EU level legislation and must transpose the Ecodesign[18] and Energy Labelling[19] Directives into national law. The individual product-specific ecodesign implementing measures and labelling delegated acts are directly applicable to Member States, meaning that all countries in the European Union follow the same regulations concerning energy-related products.

Both the Ecodesign and Energy Labelling Directives include requirements to monitor and survey the market, and enforce the regulations at a national level. Each Member State has responsibility over the market surveillance of these product regulations and must therefore organize their own monitoring, verification and enforcement processes. However, they are required to report back to the European Commission on their compliance activities and results of any testing. They are also required by law to communicate and collaborate with other national market surveillance authorities to share information and discuss common problems and potential solutions, in order to improve compliance of the market.

In Preamble 27 to the Ecodesign Directive, national market surveillance authorities are encouraged to exchange information and communicate via different platforms. This is further specified in Article 12 of the Directive "Administrative cooperation and exchange of information", where Member States are required to encourage their MSAs to collaborate with one another, and to report back to the European Commission so that it can support this cooperation and collaboration. The European Commission has therefore set up an Administrative and Cooperative (ADCO) group for both Ecodesign and Energy Labelling, where national MSAs come together twice a year to discuss compliance issues such as regulatory grey areas that can be interpreted in different manners and therefore require agreement at the European level to be enforceable. They also use this forum to share information on testing activities and results, as well as significant enforcement measures, such as product withdrawals from the market that other Member States should be aware of.

The European Model: Current Compliance Best Practices and Challenges

The European model has proved successful in increasing communication and information sharing between Member States. The following sets out certain benefits of this approach, as well as certain challenges.

- The ADCO is chaired by a national MSA, and co-chaired by another. Rather than have the European Commission responsible for the group, the MSAs are guaranteed ownership over

[17] Contribution from Mark Ellis. CLASP, Energy Policy Toolkit for Energy Efficiency in Appliances, Equipment, and Lighting (December, 2013)
[18] Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (Text with EEA relevance)
[19] Directive 2010/30/EU of the European Parliament and of the Council of 19 May 2010 on the indication by labelling and standard product information of the consumption of energy and other resources by energy-related products (Text with EEA relevance)

the group and its activities, leading them to have more buy-in to the group and its success. The European Commission participates in the group to learn what more can be done to support the MSAs in order to guarantee the benefits of the regulations. It is, however, difficult to find volunteer Chairs who are willing to take on the role for a year or more given the resources they must devote to this role.

- The European Commission hosts one meeting a year, while the Chair hosts the other. The European Commission covers the costs of at least one meeting, as well as the costs of travel and subsistence for one representative per Member State to both meetings, to encourage MSAs to attend and participate in the meetings. However, participation to these meetings can be limited, as not all Member States will send a delegate despite the offer of financial support. This can be due to a limit of resources available to the agency, making it difficult for them to send staff abroad. There may also be different agencies responsible for different activities in one Member State, making it complicated to send just one national representative.

- The European Commission supports information sharing and collaboration between Member States, by providing lists of all MSA contacts, accredited laboratory information, and by hosting electronic platforms on which to share information on testing activities, to disseminate test results, or to inform others of severe enforcement actions, such as product withdrawals from the market. However, these are not always kept up to date and the electronic platforms do not fully serve their purpose and are rarely used by MSAs, as they do not capture all the information that is necessary to keep each MSA properly informed.

- The MSAs are required to carry out testing, and to report back to the European Commission on testing carried out, results, and actions taken. However, due to the high costs of testing, several Member States have insufficient capacity to carry out testing for ecodesign and energy labelling.

Ecopliant and EEpliant: Member States Taking Action to Improve Compliance and Collaboration

Several EU MSAs recognized these challenges within the ADCO group and decided to take action to address them, having realized the value of regional cooperation.

In 2010, members of the ADCO determined that market surveillance activities undertaken at the national level were too few to make a significant impact and that, as a result, the anticipated benefits of the regulations were not being realized. The high costs of testing were deemed the main reason for lack of activities, so in order to increase resource capacity to enable more testing ten MSAs launched a project, supported with funding from the European Commission and national in-kind contributions, to seek out Member States' best practices that could increase testing capacity and effective information sharing across the region. This project was named the European Ecodesign Compliance Project, more commonly known as Ecopliant.[20]

The Ecopliant project is intended to support the delivery of the economic and environmental benefits of the Ecodesign Directive, by strengthening market surveillance within Member States and by increasing levels of compliance across the EU and EEA. The project aimed to establish a framework and support infrastructure for the cost-effective coordination of MV&E of the Ecodesign Directive.

The project examined and analyzed different practices and tools used by MSAs across the EEA and carried out a pilot coordinated market surveillance exercise, which in turn assessed the best practices identified by the project. The results of both the best practice analysis and pilot programme were combined to develop a range of 'good' practice on all stages of market surveillance activities, as well as on how best to coordinate activities between MSAs. The project produced a set of guidelines and training seminars for use by MSA personnel and created a database was created for the MSAs to share plans, results and other information about market surveillance with one another. The project partners consisted solely of EU MSAs and was led by the UK national regulator. Contributions and insights from industry and civil society were provided through an External Advisory Group (EAG) consisting of European trade associations, consumer organisations, and environmental non-governmental organisations.

[20] See more information at www.ecopliant.eu

The three year project was completed in April 2015. As a result of the project, the participating MSAs have demonstrated closer engagement within the ADCO group, and more confidence in sharing compliance information amongst each other. The Ecopliant group's goal is to pass on these outcomes to other Member States participating in the ADCO, so that the level of confidence between countries can grow within the whole EEA. Some success towards achieving these goals has been observed, as other MSAs have started to use the project deliverables, and some have even signed on to the next phase of the project. EEpliant, a second initiative supported by the European Commission, includes 13 MSA project partners who will build on the activities developed by Ecopliant, and expand the scope of the project to cover Energy Labelling.

Figure 4. European Initiatives Supporting MV&E

Initiative	Areas of Focus	Participants	Funding Sources
ECOPLIANT	• Establishing best practices • Coordinating MV&E, e.g. joint testing of products • Sharing data between members states • Training tools • Communications & dissemination	Market surveillance authorities from 10 EU Member States	75% of annual budget funded by EU
EEPliant	• Establishing best practices • Coordinating MV&E, e.g. joint testing of products • Sharing data between members states • Training tools • Communications & dissemination	Market surveillance authorities from 13 EU Member States	66% of annual budget funded by EU
ADCOs (Administrative Cooperation for Market Surveillance Group)	• Exchanging market surveillance experiences • Cooperate in testing of products • Publishing test results	Market surveillance authorities from all EU Member States	66% of annual budget funded by EU; in-kind support

Transferring EU's Lessons Learned to the Asia-Pacific Region

Certain commonalities exist between the European and APEC regions, however, there are significant differences that may affect success of initiatives that are replicated from the EU to the APEC region. These commonalities and differences were discussed amongst members of the APEC EGEE&C in early 2014. At this meeting, several economy representatives wondered how a single compliance network, supported by joint or coordinated testing would operate in a region with different markets and different legislation governing national S&L programmes. In addition, there are no requirements mandated by the APEC Secretariat to carry out compliance activities or to report back on national activities. Regardless, these economy representatives acknowledged the benefits of this type of collaborative engagement and agreed that many approaches to improving, increasing and coordinating compliance activities within the EU could be adapted and adopted to economies willing to participate in the APEC region. The benefits involved would not only be enjoyed at the national level, but also at a sub-regional or regional level.

The European approaches that could most easily be adapted to the APEC region include the following:

- Creation of a group dedicated to compliance for S&L activities, similar to that of the Ecodesign and Energy Labelling ADCO groups, that would meet twice a year to exchange best practice and to help build confident cooperative engagement within the region;

- Having a Chair and Secretariat to manage the aforementioned group from one of the member APEC economies, as is the case in Europe. This group could sit under the APEC EGEE&C and report back to the APEC Energy Working Group on progress of the collaboration, the way the ADCO groups report back to the European Commission;

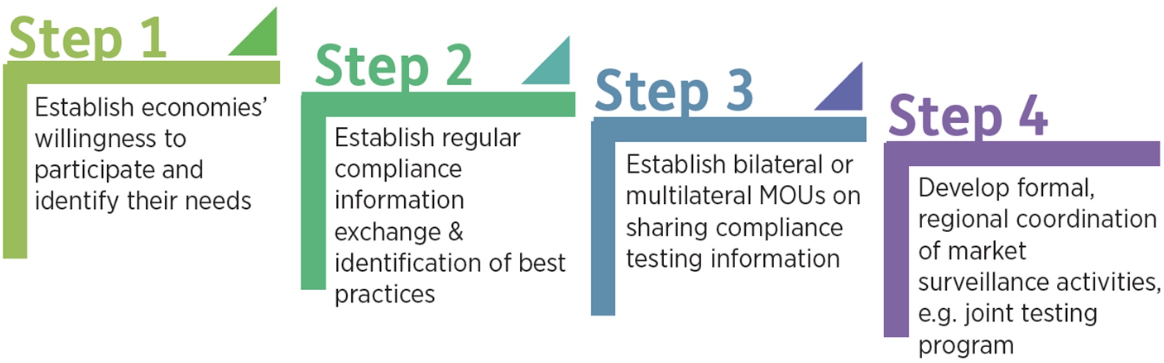
- Establishment of a database or electronic platform for information sharing across the region, accessible by all APEC enforcement authorities, similar to those platforms developed in the EU and building upon the model created by the Ecopliant project.

- Development of a joint testing project, similar to the testing activities carried out under Ecopliant, that could be supported by funding from APEC and through in-kind contributions in order to boost engagement from member economies.

Concept of a regional approach to APEC MV&E Network

Building on these approaches, representatives from the APEC EGEE&C agreed to develop a concept for a regional collaboration within an APEC MV&E network. In early 2014, members of the APEC EGEE&C agreed to adopt a light touch approach to regional collaboration, so as not to impose any burden on member economy resources, and so as not to step on national authority for compliance activity. Instead, they agreed to adopt a step by step approach that would enable a few key members to form the foundation for the network, starting with simple information exchange and sharing of best practice. In the long term, more economies would be expected to join once the success of the network is evident. The level of collaboration and cooperation would also increase over time and with additional resource contributions. This step by step approach is set out below.

Figure 5. Step by Step Approach to Regional Collaboration.



In October 2014, policymakers and MSA representatives from the APEC region gathered in Beijing for a second Compliance Best Practices Workshop, with a goal to share best practices on compliance testing and to spearhead regional collaboration on compliance efforts, and to take this concept of regional collaboration one step further.[21] Many expressed interest in launching a pilot regional MV&E effort, building on the European model, which could create a shared compliance intelligence database for signaling products that failed compliance testing, and a number of other activities to strengthen MV&E frameworks in the region.

At the workshop, a set of APEC MV&E Network Guiding Principles[22] were drafted and discussed, with the intention of using these to form the foundation for a regional network. The document expresses an intention by willing APEC economies to collaborate on a regional network focusing on sharing MV&E

[21] http://clasp.ngo/en/Resources/MVEResources/MVEPublicationLibrary/2014-APEC-Workshop-Facilitates-Collaboration-on-Compliance.aspx

[22] The principles above were initiated by the participants of the APEC Compliance Best Practice Workshop, held on 24 October 2014 in Beijing China, with support from the APEC EGEE&C, CLASP, ICA, and UL as part of their joint efforts to promote energy-efficiency in the APEC region.

information and best practices, in support of national energy efficiency S&L programmes in the Asia Pacific region. The principles define the background and the needs for such a network and will serve as the basis for future cooperation and coordination between the APEC economies, under the auspices of the APEC EGEE&C and its strategic partners.[23]

The Principles incorporate recommendations from the EU regional collaboration model, and include additional references to liaising with other regional networks; to identifying funding sources to support development of joint projects; and to encourage engagement with strategic partners that can support the network.

Potential benefits & risks for the Network

Partners of the Network are expected to benefit from this project in the following ways:

- An accelerated adoption of MV&E best practices, as they will be learning from their partners rather than developing practices from scratch;

- Reduced costs for data collection and compliance testing, as they will be sharing information on those products tested by other economies so they can better target their testing and compliance activities;

- Improved compliance by coordinating and leveraging shared compliance market intelligence with and from partnering APEC economies;

- Increased potential to align standards for products within the region, particularly sub-regions of the APEC, to facilitate coordinated compliance activities – thereby reducing burden of testing on manufacturers and importers as well as for the enforcement authorities;

- The potential to link to and collaborate with other networks, including the EU ADCO, to build a bigger stronger network of MVE practitioners that can share compliance information amongst regions across the globe.

- Skill building for MSA staff, through sharing of best practice, with support for smaller economies who have fewer resources to conduct testing.

Conclusion

Given their regional proximity and their very similar markets, Australia and New Zealand have been collaborating on energy efficiency policies for appliances and equipment for years and are therefore huge proponents of a regional network. They have therefore been paving the way for this network with the support of the APEC EGEE&C's strategic partners. China has expressed support for this initiative and, along with Australia and New Zealand, will be seeking support from the APEC Secretariat to initiate this project in the next year.

Some challenges lie ahead. Any APEC MV&E Network will have to take the time to grow in terms of scope and participants. Building on the lessons learned from the Ecopliant project, success will not be possible if ambition is set too high too quickly. A smaller group of participants will need to take the lead, first by sharing information and next by collaborating on compliance activities. These key economies will have to invest in-kind resources in addition to any support provided by other organisations, in order to become fully invested in the project. The responsibility of involving and bringing in further participant economies will fall to the founding partners. The priority for compliance will have to be highlighted at the higher levels of government and political, language, and capacity hurdles will have to be overcome.

However, the benefits involved outweigh the hurdles – by helping to increase compliance levels, this project has the potential to increase savings from S&L programmes by 25% in a region where energy

[23] These partners currently include CLASP, the International Copper Association and Underwriter Laboratories, who are all observers to the APEC EGEE&C and have supported this regional compliance effort from the start.

consumption is rising rapidly. As the APEC region produces so many products intended for export, the EU market will equally benefit from greater compliance rates – not only due to more compliant products being exported into the country, but also due to better communication pathways between a European and APEC compliance network.

Policies and Programmes

Blurring Boundaries of Market Transformation activities: Linkages among Awards, Procurement, and Incentives

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Abstract

Market transformation programs are critical to expanding the availability of top efficiency appliances, lighting and equipment. The Super-efficient Equipment and Appliance Deployment (SEAD) Initiative, a voluntary multinational government collaboration of the Clean Energy Ministerial, undertakes work in three areas of the early stages of market transformation: awards, procurement, and incentives. Each of these areas stimulates the market for energy-efficient products by motivating sellers or purchasers of a product to make a more energy-efficient choice.

This paper will review how policies transform the market for energy-efficient technologies, and define the "market stimulation" early stages of market transformation. It will also examine how sequential integrated market stimulation policies can affect greater change than separate application of each type of policy.

Finally, this paper will take a closer look at three SEAD projects – one each in awards, procurement, and incentives – in order to investigate how these three types of programs can more successfully feed into each other to further enhance realized energy savings. The paper will explore these linkages and other potential connections among market stimulation program areas through these three projects. In addition, for each program area, the paper will describe the potential impacts of making those connections on stakeholders including governments (national or local), utilities, manufacturers, and consumers.

Introduction: Market Transformation for Energy Efficient Technologies

Market transformation is a term that describes the progression of a new technology or innovation from research and development through to mass adoption. The stages that comprise this progression are shown in Figure 1. A number of policy interventions, shown across the top of Figure 1, can accelerate the transition of new products to the next market stage.

In the early stages of market transformation, the main method for achieving this acceleration is through *market stimulation*.[1] Market stimulation creates economies of scale, which lower costs for consumers, by increasing demand for new products in one of three ways:

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[1] The authors selected the term "market stimulation" to reflect the similarities to existing programs, such as programs within the US Department of Energy's Building Technologies Office (BTO). BTO's

(1) Singling out new, best available technologies through awards,
(2) Artificially lowering prices for consumers through incentives, or
(3) Requiring the purchase of energy-efficient products through procurement programs.

As demand increases towards a critical mass, manufacturers' production costs fall which in turn lowers prices and increases cost effectiveness. Then, as products become cost-effective, they move towards mass adoption.

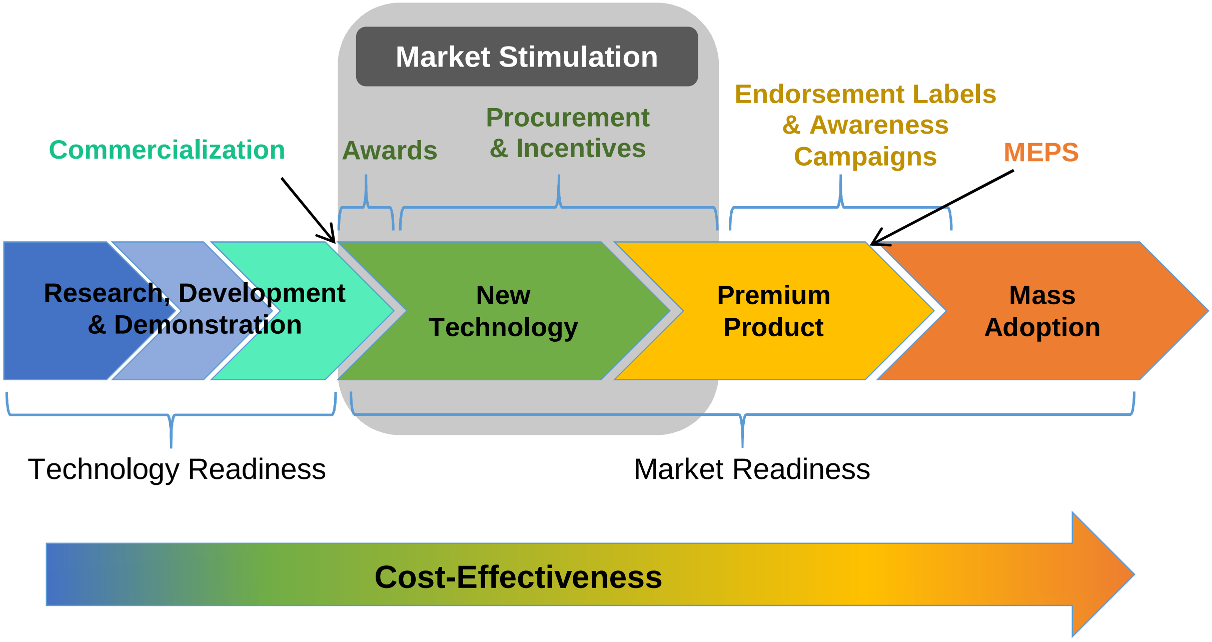

Figure 1: Market Transformation Stages and Target Policy Interventions

At every stage along the path of market transformation, consumer choice and behavior can have a significant impact on the net energy savings achieved from the uptake of energy-efficient technologies. For example, the rebound effect and free ridership both decrease overall energy savings, and program spillovers increase overall energy savings. [1] This paper examines the uptake of energy-efficient technologies themselves, rather than on the energy savings that result, and therefore will not focus on these effects.

New Technology and related market interventions

In the New Technology market stage, manufacturers are selling a newly innovated product, but it is purchased mainly by trendsetters and early adopters who are demonstrating the utility and value of the new technology. At this stage, the technology is not necessarily cost-effective – manufacturers are still producing a small quantity, and so the forces that will bring prices down later – economies of scale and learning effects – have not yet taken place. For all of these reasons, technologies at this stage are not expected to capture a significant market share.

At the early part of this stage, Awards can be an effective policy intervention to identify products that are transitioning from demonstration to new technology. By bringing attention to the best available technologies, Awards can motivate manufacturers to increase the market share of products at a certain energy efficiency level, and can encourage trendsetters and early adopters to notice and purchase the products. A bit further along in the new technology phase, procurement and incentive programs can motivate the purchase of these new technologies by consumers and large institutions

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market stimulation programs help grow new technologies, thus bridging the gap from research and development to building codes and appliance standards. More information is available online at: http://energy.gov/eere/buildings/key-activities-energy-efficiency with an inclination for using leading-edge, energy-saving technologies. These programs create niche markets for new technology and premium products, amplifying the energy-saving impacts that these products can have.

Taken together, these policy interventions – awards, procurement, and incentives – constitute *market stimulation*. Ideally, they increase the demand for (and therefore the production of) cutting-edge energy-efficient products, leading to accelerated reductions in costs, improved cost-effectiveness, and progression from research and development to mass adoption.

Towards Mass Adoption

As product costs continue to fall due to greater production and manufacturer learning, new technology products become premium products at the top end of the market within their product category. These better-than-average products often have a price premium due to high energy efficiency being bundled with other features that consumers want. These products are often cost effective, but not always. Endorsement labels and consumer awareness campaigns can help early and late majority consumers identify and purchase these products.

Finally, once products are cost-effective, mass adoption leads the efficient technology to become standard on the market or, if minimum energy performance standards (MEPS) are put in place, a requirement.

Figure 2 shows a technology diffusion curve [2] with the various categories of consumers that tend to purchase technologies in each market stage along with the types of policy interventions to which they are therefore likely to respond. The portion of the market that may be influenced by market stimulation policies – awards, procurement, and incentive programs – are those at the early stages of technology diffusion. Trendsetters and early adopters will be influenced by all three of these policy types, and some of the early and late majority will be influenced by procurement and incentive programs.

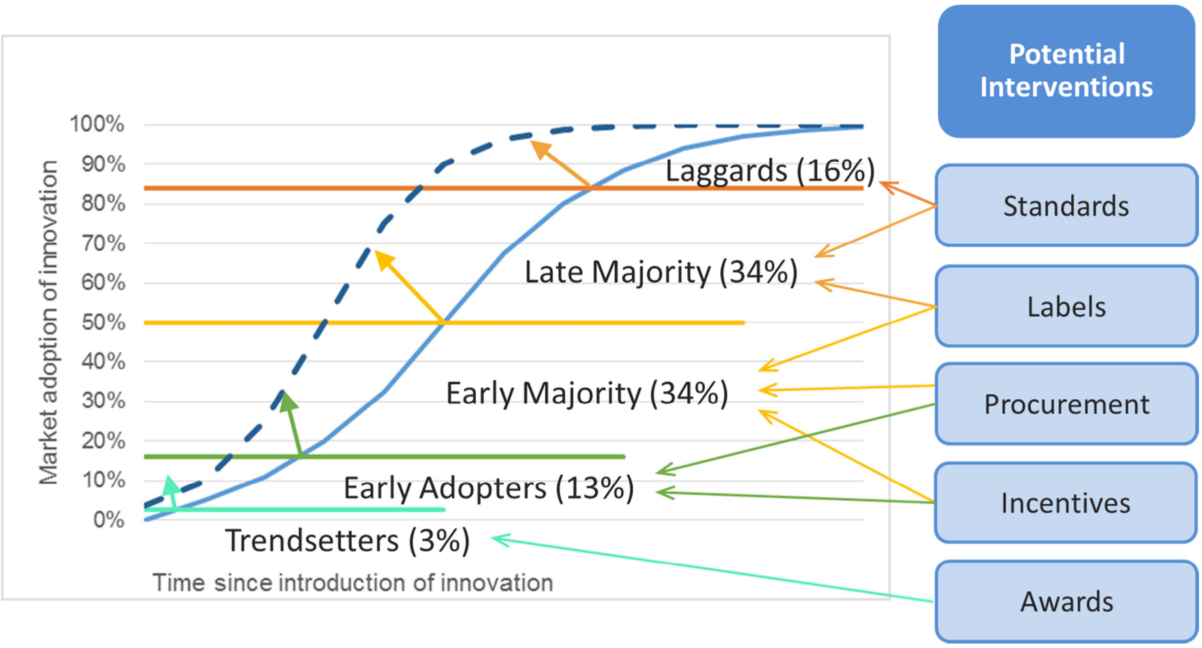


Figure 2: Technology Diffusion Curve and Target Policy Interventions [2]

The technology diffusion curve in Figure 2 is shown with time on the x-axis. Over time, manufacturers learn how to improve their processes and take advantage of economies of scale, and this technological learning leads to cost reduction. [3] Policy interventions for market stimulation at the early stages of market transformation reduce costs, improve cost-effectiveness, and accelerate progression along the technology diffusion curve. In Figure 2, the market stimulation policy interventions accelerate market adoption from the slower solid blue diffusion curve to the faster dotted blue diffusion curve. Ultimately, therefore, market stimulation leads to accelerated market transformation and earlier implementation of standards and labeling policies.

A Cyclical Process

Once new standards and labeling policies are in place, manufacturers will create new innovations to again push the envelope for energy efficiency. Ultimately these collective policies create continuous cycle of improvement for energy efficient technologies. [4]

As a product with new energy efficiency innovations comes to market, it will go through a cycle of increasing demand, lowering costs, and improving cost-effectiveness. Market stimulation programs therefore are useful each time new innovations provide a product with significant energy efficiency improvements. Major innovations will initially increase manufacturing costs anew and therefore require market stimulation programs to catalyze the lower prices that drive market demand. It is important to note that this cycle will happen many times for any product, as research and development lead to new innovations and efficiency gains.

For example, a number of innovations have led to major energy efficiency improvements for residential refrigerators. In the US, the Super-Efficient Refrigerator Program used an Awards program in the mid-1990s to motivate manufacturers to sell super-efficient refrigerators. With a US$ 30 million prize, manufacturers supplied refrigerators that were 25 to 50 percent more efficient than existing products on the market and did not use CFCs. [5] [1]

Since then, utilities across the US have provided fiscal incentives for the purchase of energy-efficient refrigerators. The efficiency levels that qualify refrigerators for these market stimulation programs continues to rise as the product mix continues to become more and more efficient. Incentives and other market stimulation policies paved the way for new standards implemented in 1993, 2001, and 2014, and prices of refrigerators have continued to fall despite the increases in efficiency. [6]

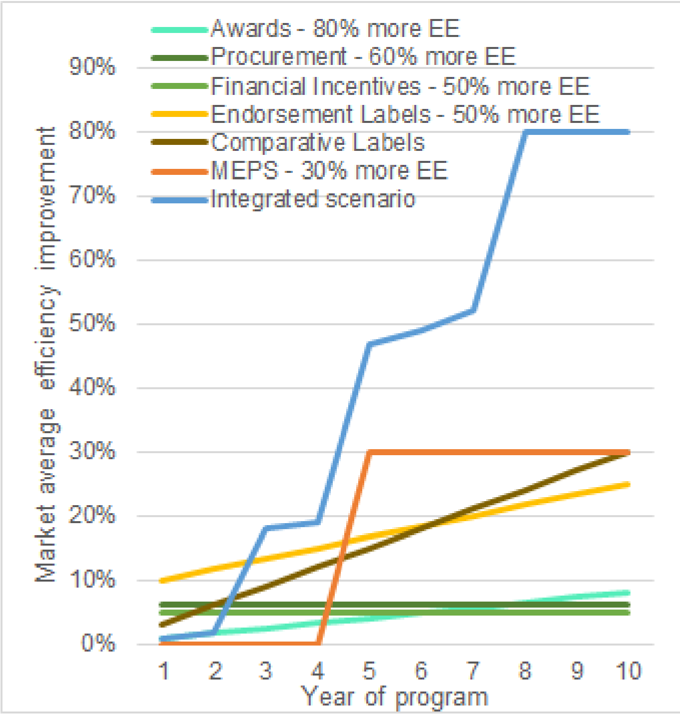
The Sum is Greater than the Parts: Integrating Market Transformation Activities

While each policy intervention causes some transformation of the market, it is even more effective for market transformation policies to be implemented in a coordinated way to shepherd products through the pathway of adoption. Figure 3 illustrates this point by showing each potential policy intervention on its own, and then showing an integrated scenario that combines these policy interventions. In this case, the integrated scenario uses the assumptions laid out in the sample policy implementation timeline. All percentage improvements outlined in this scenario are hypothetical.

Figure 3 shows that the earliest interventions – awards, procurement, and financial incentives – have the largest energy efficiency improvements (50-80%). However, because these market stimulation interventions only reach innovators and early adopters – about 15% of the market at most – they each only improve the average market efficiency by 1-8%. On the other extreme, MEPS improve the energy efficiency of the product by only 30%, but because they are mandatory, that results in a 30% improvement in the average market efficiency.

When these policy interventions are implemented in the sequence outlined in the sample policy implementation timeline, the cumulative effects (integrated scenario) are significantly more than any individual policy. Furthermore, the total timeline is accelerated, as the early market transformation policies began the process of bringing down costs, enabling the later policies such as MEPS to be politically palatable.

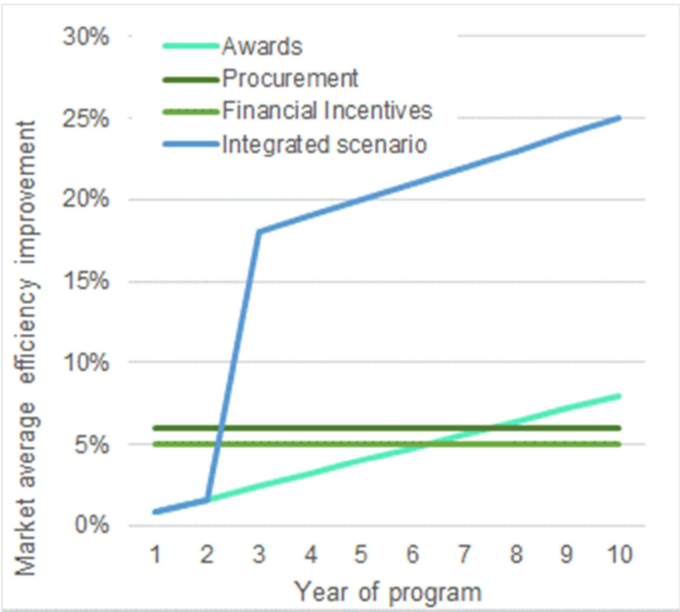
Figure 4 shows the same information as Figure 3 but focuses on the market stimulation interventions. Each policy intervention on its own might achieve less than 10% improvement on the market average efficiency because of low market adoption. An integrated market stimulation policy approach could improve the market average efficiency by 20-25% by (1) adding the effects of each intervention on its own, and (2) reaching more of the early majority (in addition to innovators and early adopters) as the cost-effectiveness of the product improves with increased production.



Sample Policy Implementation Timeline:

- **Year 1:**
  Announce **awards** to identify best available technology (BAT)
- **Years 3 & 4:**
  Target BAT through **financial incentives** and **procurement**
- **Years 5, 6, & 7:**
  Increase market share through **comparative** and **endorsement labels**; technological learning reduces prices
- **Year 8:**
  Introduce **MEPS** at initial BAT level

Figure 3: Example Integrated Energy Efficiency Policies for Market Transformation: All Policies



Sample Policy Implementation Timeline:

- **Year 1:**
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Figure 4: Example Integrated Market Stimulation Policies

Integrated Market Stimulation Policies: A Hypothetical Example

As an increasing number of countries turn to appliance energy efficiency as an element of actions against power crises and climate change, there are ever more opportunities to design integrated policy portfolios of market stimulation activities. Though an integrated approach could take many forms, one potential example timeline is outlined below.

1. A national (or regional) government prioritizes product categories for which improvements in energy efficiency would have high impacts on electricity demand or peak load demand.
2. For a selected product category, a national awards program identifies the most efficient products on the market. If desired, one criterion could be local production or assembly of those products.
3. The national government provides financial incentives to manufacturers or consumers to increase the purchase of award-winning products. If local production is a criterion, the government provides upstream incentives to manufacturers of award-winning products to subsidize their production. Otherwise, the government provides incentives to purchasers/consumers.
4. Simultaneously, if relevant for the selected product category, government agency procurement programs specify preferred purchase of award-winning products, or set energy efficiency criteria at a level consistent with the energy consumption of award-winning products.

This kind of comprehensive program is an exciting goal, but does face several potential barriers. For such a program to be successful, selected products must have significant potential energy savings or peak load abatement as well as significant potential demand in order to transform the market.

In addition, an integrated program would require political will to enable multi-year planning and coordination among multiple government ministries. An awards program would likely be managed from an energy-related ministry, an upstream incentive might be administered by an industry ministry, and procurement programs are often run by an administrative or competition-related agency. For an effective integrated market stimulation policy portfolio, the sequence of each phase would have to be agreed in advance and implemented by each agency in turn, with some flexibility for unforeseen delays and transparent communication throughout.

A significant benefit of this type of program structure is the potential to strengthen local industries' production of energy-efficient products. Industry ministries are often seeking ways to invest in local industries. Moreover, local industries in developing countries can struggle to keep pace with global manufacturers on the development of energy efficient products, and this type of policy portfolio can improve local industry competitiveness ahead of potential minimum energy performance regulations.

Potential linkages among existing SEAD activities

Existing activities within the SEAD Initiative seek to transform the market for energy-efficient products, but so far have done so within individual policy areas rather than in a coordinated fashion across market stimulation policy streams. This section will take a closer look at three SEAD projects – one each in awards, procurement, and incentives – in order to investigate how these three types of programs can more successfully feed into each other to further enhance energy savings. For each activity, this section will describe the potential impacts of making these connections on stakeholders including governments (national or local), utilities, manufacturers, and consumers.

Awards: The SEAD Global Efficiency Medal for lighting products

Background about the SEAD Global Efficiency Medal competitions

The SEAD Global Efficiency Medal competition is a global competition that encourages the production and sale of super-efficient equipment, appliances, and electronics by identifying the most efficient product in each category in four regions, as well as an overall global winner. The first awards were given in 2012 to manufacturers of energy-efficient flat-panel televisions, followed by 2013 awards for displays and 2014 awards for line-start electric induction motors. Most recently, awards were given in May 2015 for lighting products with the highest efficacy in selected categories.[2]

This winner-takes-all competition seeks to advance efficiency improvements by:

- Recognizing products with the best energy efficiency;
- Guiding early adopters who want to purchase the most energy-efficient products; and
- Demonstrating the levels of efficiency that are achievable with existing and new technologies.

The benefits of winning an award in the competition include:

- Exposure and global recognition for products, providing external confirmation of energy efficiency credentials;
- Strengthened reputation as an award winning manufacturer of super-efficient products;
- Use of a Global Efficiency Medal award logo on packaging and marketing materials; and
- Attendance at an awards ceremony to showcase the victory.

The SEAD awards complement existing national and multinational labeling programs, such as ENERGY STAR, that set performance thresholds for energy-efficient products.

Manufacturers self-nominate products for consideration for the Global Efficiency Medal in any number of categories and regions. SEAD then analyzes the nominations for presumed winners, procures samples through random sampling from the manufacturer or purchasing products from the market, and performs testing to verify the manufacturer energy performance claims.

The Lighting Awards

On 12 May 2014, the SEAD Initiative launched its fourth Global Efficiency Medal competition, which recognized and awarded highly energy-efficient lighting products. Lighting products were selected as an award category because of the large impact lighting has on overall electricity consumption. Grid-based lighting accounts for about 15% of electricity consumption globally. [7] In 2006, the cost of providing lighting service globally was USD 360 billion, or roughly 1% of global GDP. [8]

Regional Awards	GLS Lamps					Directional Lamps		Planar Luminaires	Downlight Luminaires	
	Commercially Available			New Technology		Commercially Available		Commercially Available	Commercially Available	
	≥800 lumens 2700-3000K CCT	≥800 lumens 4000-5500K CCT	≥700 lumens 5500-6500K CCT	≥1500 lumens 4000-5500K CCT	≥1300 lumens 5500-6500K CCT	Low-voltage ≥600 lumens 2700-3000K CCT	Mains-voltage ≥600 lumens 2700-3000K CCT	600mm x 600mm (2ft x 2ft); ≥2000 lumens	≤51mm (2 in) ≥700 lumens 3000K CCT	≥102mm (4 in) ≥1500 lumens 4000K CCT
AUSTRALIA	• 230V	• 230V		• 230V		• 12V	• 230V	•	•	•
EUROPE	• 230V	• 230V		• 230V		• 12V	• 230V	•	•	•
INDIA	• 230V	• 230V	• 230V	• 230V	• 230V	• 12V	• 230V	•	•	•
NORTH AMERICA	• 120V	• 120V		• 120V		• 12V	• 120V	•	•	•
GLOBAL AWARDS	• 230V	• 230V		• 230V		• 12V	• 230V	•	•	•

Figure 5: Categories for the 2015 SEAD Global Efficiency Medal for lighting products

Categories for the lighting awards were determined through a consultation process with policymakers and technical experts in the months leading up to the awards launch. These categories, shown in Figure 5, represent common lighting products found in participating regions for which a transition to energy-efficient lighting would have a significant energy savings impact.

[2] To win the Global Efficiency Medal for lighting, products also had to meet a number of other minimum quality criteria that ensured that the winning products did not sacrifice quality for efficiency.

Integrating the SEAD Lighting Awards with Incentive and Procurement Programs

While the SEAD lighting awards identified lighting products with extremely high efficacy, the opportunities to influence product purchasers have been limited. Awareness of the Global Efficiency Medal is low, so inclusion of that logo on marketing or packaging materials has limited ability to stimulate the market for these super-efficient products.

To increase the impact of the SEAD lighting awards, linkages could be made with utilities, many of which have incentive programs for lighting products. For tiered incentive programs, a new top tier of consumer or retailer cash rebates might be possible with a specification inspired by the efficacy (and quality) of award-winning lighting products. Although the winning products were required to meet a cost threshold, these cash incentives would improve the cost-effectiveness of these high efficacy technologies, which could help move them along the diffusion curve from early adopters to the early majority which is more sensitive to first costs. By increasing the production volume, manufacturers would then be able to bring down costs further, making the products (with or without subsidies) more palatable to the late majority consumers.

In addition, linkages could be made with some procurement programs. Some procurement programs, such as the federal procurement program in the US, have a small fraction of their portfolio for which purchasers can purchase best-in-class technologies that go beyond the least lifecycle cost level. In addition, for some niche procurement instances with very high energy prices (such as national parks, islands, or call boxes), best-in-class technology would be more cost effective. In each of these instances, procurement of award-winning products could also increase the overall demand for these energy-efficient technologies.

Linking the awards with incentive and procurement programs would impact utilities, manufacturers, and consumers. For utilities, reduced electricity loads from lighting can help ease the strain on peak loads. In addition, for utilities that are required to meet certain electricity reduction goals, the proliferation of efficient lighting can be a large step towards meeting those goals.

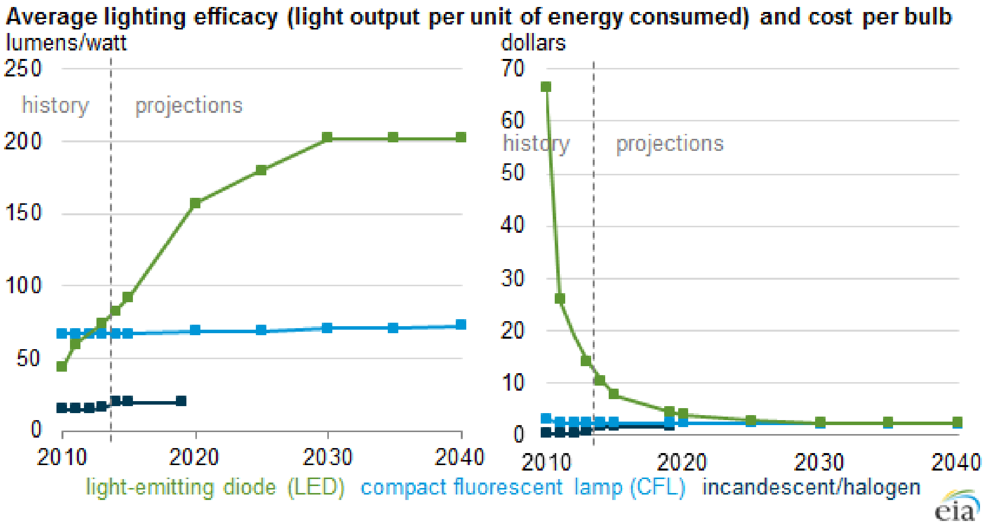

Figure 6: Average lighting efficacy and cost per bulb [9]

Manufacturers would be greatly impacted – as shown in Figure 6, even as the efficacy of LED lamps and luminaires have skyrocketed in recent years, the first cost of these products have come down dramatically. However, these products still usually have higher costs than other lighting technologies. Therefore, further reducing the costs of the highest efficacy lighting products will increase production volume for manufacturers of these products. Finally, more consumers will be likely to purchase super-efficient lighting products with lower first costs that increase the overall cost-effectiveness of the products.

Procurement: The SEAD Street Lighting Evaluation Tool

Background about the SEAD Street Lighting Evaluation Tool

Street lighting is typically one of the largest sources of energy consumption under a municipality's direct control. A rapidly changing product market, including the introduction of LED fixtures and other advanced technologies, allow for significant energy savings, but also make proper lighting design and careful evaluation of fixture choices all the more important. The SEAD Street Lighting Tool provides a quick, easy way for government procurement officials and lighting specialists to evaluate the light quality, energy consumption, and life cycle cost of efficient street lighting options.

The SEAD Street Lighting Tool is a free, easy-to-use calculator that can help purchasers make more informed choices regarding street lighting fixtures to help achieve up to 50 percent in energy savings. Supported by Mexico's National Commission for Energy Efficiency, India's Bureau of Energy Efficiency, Natural Resources Canada, Swedish Energy Agency and U.S. Department of Energy, the tool is designed to make the fixture evaluation process easier by assisting street light purchasers with evaluating light quality, energy use and costs for the most common road layouts.

This Excel-based tool calculates the expected energy use, light performance, and lifecycle cost of street lighting upgrades for the most common road configurations. It evaluates the luminance and illuminance, energy consumption, and life cycle cost for both LED and conventional fixtures on many common road layouts, and provides several unique benefits to users:

- **Small Municipality or First-Time User:** The tool intentionally simplifies the photometric analysis to enable first-time users to perform a first-level assessment of lighting options using common road configurations.
- **Experienced Lighting Designer:** The SEAD tool is designed to make prescreening fixture choices faster and easier, and can assist lighting designers with analyzing tens or hundreds of fixture choices in a single batch for a particular road and pole configuration.
- **Manufacturer:** Manufacturers often receive requests to recommend the best fixture of those they sell for a particular road configuration, and can use the SEAD tool to optimize this selection process and provide consistent recommendations across their organization.

Integrating the SEAD Street Lighting Tool with Awards

For additional impacts, the SEAD Street Lighting Evaluation Tool could be informed by a street lighting award program recognizing the most energy-efficient, high quality fixtures for various road layouts. Award-winning fixtures could be included in the tool as sample fixtures, or anonymized fixtures with data that reflects the energy use of the winning products. This would then provide these super-efficient options to tool users. Because these fixtures would still be subject to the tool methodology and analysis, those award-winning fixtures that were suited to the users' specific road configuration would be shown to be a good fit (along with any other fixtures the user enters).

Linking the SEAD Street Lighting Tool with awards could impact local governments, utilities, and manufacturers. Municipal governments are responsible for managing street lighting, and are one of the main audiences for the tool. Policymakers who use the tool to evaluate street lighting options may see the award-winning fixtures proposed as potential low life-cycle cost options, and may then consider installing those fixtures in their municipality. These fixtures could also be marked as award winners, which would indicate that SEAD had tested them and verified their performance. Selection of these fixtures could ultimately save local government resources in future electricity payments.

For utilities, especially those that are required to meet certain electricity reduction goals, the proliferation of more efficient street lighting can be a large step towards meeting those goals.

Manufacturers with award-winning products could gain free, international advertising of their energy-efficient street lighting products directly to municipal policymakers responsible for purchasing those products.

Integrating the SEAD Street Lighting Tool with Incentives

The SEAD Street Lighting Tool allows users to enter fixture-specific information before analyzing products. This allows for more accurate light quality and life cycle cost outputs. If subsidies or rebates are offered, users can enter this information into the tool and life-cycle costs will be adjusted accordingly. This can help users make the business case for more efficient fixtures when incentives are offered. The tool also streamlines the procurement process because a separate tool or calculation is not needed to determine the impact on payback time.

Incentives: The LBNL Energy Efficiency Revenue Analysis (LEERA) model

Background about the LEERA model

Many countries around the world subsidize electricity consumption, which promotes increased and inefficient energy consumption. Countries that subsidize electricity, including a number of emerging economies, have limited options to improve end-use efficiency without raising consumer costs. Reducing subsidies may not be politically feasible or desirable, as doing so would directly raise consumers' electricity costs. Strengthening appliance and building efficiency standards also often imposes a new cost on consumers. In addition, financing appliance efficiency incentive programs is a challenge for many governments.

Faced with these obstacles, many countries are turning to appliance efficiency incentive programs as a viable way to reduce energy use without altering subsidies or increasing energy performance standards. The LEERA model is a tool to help governments with electricity subsidies design revenue-neutral appliance efficiency incentive programs.

The LEERA model helps policymakers design incentive programs that can be financed entirely by revenue generated from end-use efficiency improvements, such as avoided subsidies. [10] The model provides key data for decision makers on:

- Energy savings that can be realized through efficiency improvements;
- Financial savings from avoided subsidies; and
- Targeted incentive levels (i.e., the percentage efficiency improvement for a given appliance).

The model calculates the financial and energy savings that governments will accrue from the deployment of more efficient models of appliances. It then draws on SEAD's techno-economic analyses to calculate the efficiency improvements that can be achieved for specific appliances. The model also suggests incentive levels for more efficient models of each product.

For example, in Mexico, policymakers are planning to give away 14 million LED LCD televisions as part of their transition to all digital terrestrial TV signals. If the government replaces analog CRT TVs with super-efficient LED-LCD TVs, it can reduce TV energy consumption by 3.5 TWh/yr (roughly equivalent to the electricity generated by a 500 MW power plant). Further, the government could save up to US$877 million (MX$11.5 billion) in subsidies from such a replacement program even if these superefficient TVs are given away for free.

Integrating the LEERA model with Procurement Programs

To realize additional energy savings, the LEERA model could include national-level procurement programs for products that are applicable to federal procurement as well as being relevant to consumers. This would increase the aggregated demand for the selected product, which could result in lower purchase prices. In addition, the federal government pays 100% of the electricity used by federally-procured products. Therefore, the cost savings from federally-used products could increase the revenue available to incentivize consumer purchases of efficient products.

Linking the LEERA model with procurement programs could impact national and local governments, utilities, manufacturers, and consumers. National and local governments would save on electricity costs following the procurement of energy-efficient products. In addition, the national government would have more self-financed revenue for consumer-facing incentive programs. As a result, either more consumers would benefit from the same level incentive, or the same number of consumers would benefit from a greater incentive, to purchase energy-efficient products.

For utilities, depending on the selected product, reduced electricity loads could help ease the strain on peak loads. In addition, for utilities that are required to meet certain electricity reduction goals, the proliferation of efficient lighting can be a large step towards meeting those goals.

Manufacturers would see even larger demand for energy-efficient products through the aggregation of federal procurement and consumer-facing incentive programs. This could incentivize manufacturers to prioritize the production of the selected energy-efficient products, leading to reduced costs for any consumers who were not eligible for the incentive or who wanted to purchase the same type of product at a later time.

Conclusion

In the early stages of market transformation, the main method for achieving this acceleration is through *market stimulation*, or increasing demand for new products in one of three ways:

(1) Singling out new, best available technologies through awards,
(2) Artificially lowering prices for consumers through incentives, or
(3) Requiring the purchase of energy-efficient products through procurement programs.

As demand increases towards a critical mass, production costs fall which in turn increases cost effectiveness. Then, as products become cost-effective, they move towards mass adoption.

While each policy intervention causes some transformation of the market, it is even more effective for market transformation policies to be implemented in a coordinated way to shepherd products through the pathway of adoption.

When these policy interventions are implemented in the sequence outlined in the sample policy implementation timeline, the cumulative effects (integrated scenario) are significantly more than any individual policy. Furthermore, the total timeline is accelerated, as the early market transformation policies began the process of bringing down costs, enabling the later policies such as MEPS to be politically palatable.

Existing activities within the SEAD Initiative seek to transform the market for energy-efficient products, but so far have done so within individual policy areas rather than in a coordinated fashion across market stimulation policy streams. SEAD projects that focus on awards, procurement, and incentives can more successfully feed into each other to further enhance energy savings and to have greater impacts on governments (national or local), utilities, manufacturers, and consumers.

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Implementation of Green Public Procurement in Germany – results and conclusion from a monitoring study at the example of the city of Berlin

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Abstract

Public authorities spend a significant amount of money for goods and services: in Germany 300 billion Euros annually[1], in the city of Berlin alone around 4-5 billion Euros each year are spent.[2] By directing this spending power towards the purchase of products and services with lower environmental impacts, they help not only to drive the market for greener products and services but also make an important contribution to sustainable consumption and production (SCP). In addition, by taking into consideration all costs over the entire life cycle, green procurement has also economic advantages.

Since January 2013 the regional authorities in Berlin are obliged to take into account environmental impacts when procuring products and services with an acquisition value of 10.000 Euros and more. Against this background the senate administration of Berlin commissioned the Oeko-Institute to carry out a survey to monitor the implementation and the acceptance of the new regulation. In this way, obstacles and possible areas of improvement arising in the practical implementation of the regulation will be recognized.

The paper will present the economic advantages of green public procurement. Therefore, the life cycle costs of environmentally-friendly products and services are calculated and compared to the life cycle costs of conventional products and services. In addition to the pure acquisition costs, life-cycle costs cover also the costs of use, maintenance (so called operation costs) and disposal. In addition to the costs, the environmental impacts of the procurement options are compared, for example, resource consumption or greenhouse gas potential.

Methodological background

To determine the cost savings of green public procurement in comparison to conventional public procurement, life cycle cost calculation was used as methodological bases. With the life cycle cost calculation, all relevant costs are determined, that are caused by a product throughout its entire product life cycle. Also "hidden" costs like for example costs for maintenance or disposal are considered.

To determine the environmental relief, the environmental impacts of each product were calculated. Regarding electrically-powered devices, the focus was based on the CO_2 emissions during the use phase. Therefore the CO_2 emission factor for electricity in Germany was used (655g CO_2e/kWh). The CO_2 equivalents that are associated with the energy consumption of a device are calculated by multiplying the energy consumption with the emission factor.

Regarding non electrically-powered devices, LCA studies were used to present further environmental impacts, for example consumption of wood and water for the product group copy paper.

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1 http://www.bmwi.de/DE/Themen/Technologie/Rahmenbedingungen/innovation-beschaffungswesen.html
http://www.bmwi.de/EN/Topics/Technology/Strong-policy-framework/fostering-innovation-through-public-procurement,did=421222.html

2 http://www.stadtentwicklung.berlin.de/service/gesetzestexte/de/beschaffung/
no English link available

Determination of the environmental benefits and costs

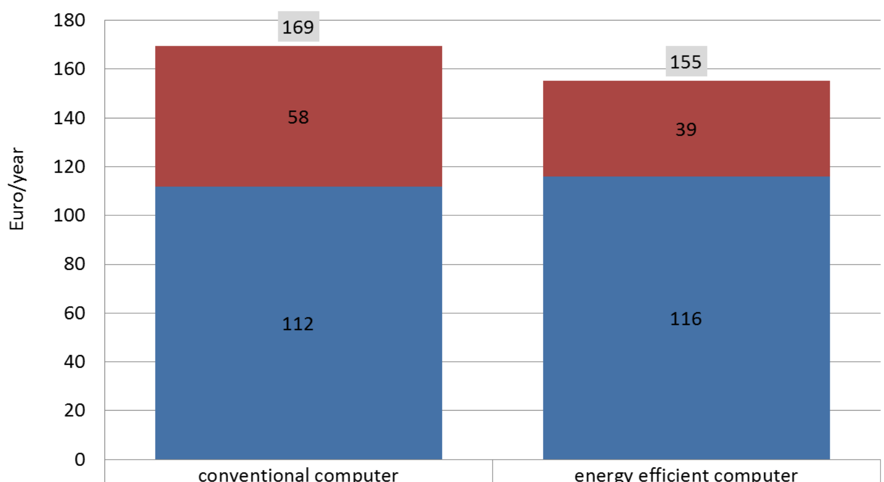
In the survey Gröger et al. 2015 the environmental benefits and costs of 15 different product groups are determined. To illustrate the environmental and economic advantages of green public procurement, this paper focuses only on three exemplary product groups: computer, copy paper and street lighting. For each product group the life cycle costs as well as the environmental impacts are calculated.

Computer

As an example a typical desktop computer for daily office use is taken into account. Regarding the energy consumption of the computer, it was assumed that the conventional one refers to the minimum requirements of the ecodesign directive for computers and servers (directive 617/2013). Computers that are sold in the European Union have to meet these requirements. Regarding the energy efficient computer it was assumed that the energy consumption meets the requirements of the ecolabel Blue Angel for computer (edition 2014). The Blue Angel[3] is an ambitious ecolabel and covers around 20-30% of the most environmental-friendly devices on the market.

The purchase price of conventional and energy efficient computers are quite similar. With similar performance characteristics and features the purchase price of the conventional computer is 335 Euros and the cost of the energy efficient computer 348 Euro. So, the energy efficient computer is around 4% more expensive than the conventional alternative.

However, the higher purchase price is compensated by the energy savings. The life cycle costs that consist of the purchase price and the energy costs, of the energy efficient computer are 8 % lower than the life cycle costs of the conventional computer.



	conventional computer	energy efficient computer
Life cycle costs per year	169	155
Annuel energy costs	58	39
Annual acquisition costs	112	116

Figure 1: Annual life cycle costs of a conventional and an energy efficient computer over a period of three years

[3] The Blue Angel is organized by the federal government of Germany. Regarding computers, the requirements not only cover the energy consumption but also a long-lived and recyclable design and the avoidance of environmentally harmful materials.

Regarding the environmental impacts the savings are even higher. The energy consumption of the energy efficient computer leads to a global warming potential of 85 kg CO_2 equivalents. The energy consumption of the conventional computer leads to a global warming potential of 126 kg CO_2 equivalents. That represents savings of CO_2 equivalents of 32 %.

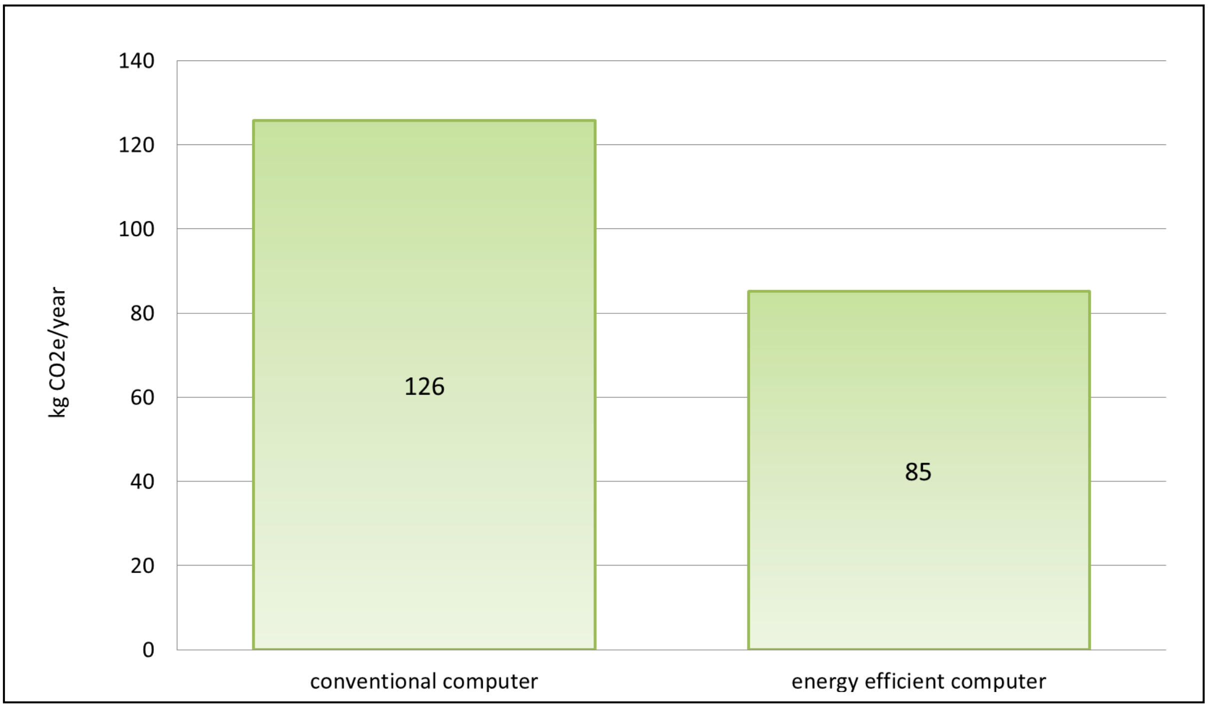


Figure 2: Annual global warming potential of a conventional and an energy efficient computer

Assuming a public authority with 1,000 employees who work with computers, 41 tons of CO_2 equivalents could be saved each year by using energy efficient computers.

In the case of Berlin it can be assumed that 50.000 Computers are in use in public authorities. By purchasing energy-efficient computers Berlin could save about 2,000 tons of CO_2 equivalents each year.

Paper

Some public authorities already use recycling paper that is made from 100% recovered paper. To show the environmental effects of the use of recycling paper it is compared to paper composed of fresh fibre as conventional alternative. Regarding the life cycle costs of the paper, the purchase price of the recycling paper is lower than the purchase price of the conventional paper (13%).

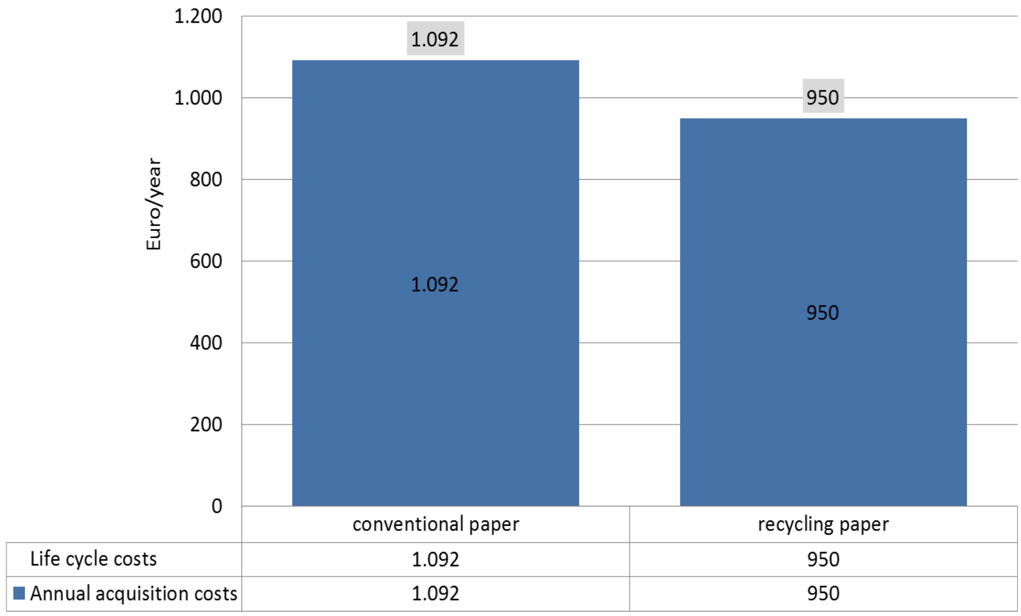


Figure 3: Annual life cycle costs of 100.000 sheets of conventional and eco-friendly paper

Regarding the environmental impacts the global warming potential as well as the water and wood consumption were considered as indicators. The production of recycling paper causes 15% less greenhouse gas emissions than the production of paper with freshfibres. In addition, 61% less water is used for the production of recycling paper than for the production of conventional paper. And as recycling paper consists of 100% of recovered paper, it is not linked with any use of wood whereas for the production of conventional paper 1,500 kg wood per year is needed.

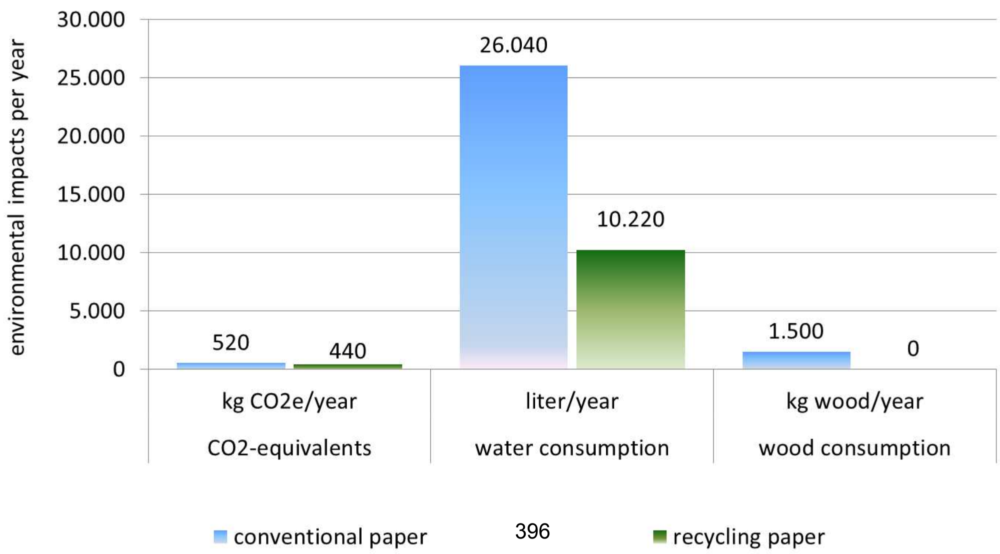


Figure 4: Annual environmental impacts of 100.000 sheets of conventional and eco-friendly paper

Assuming an annual consumption of 100,000 sheets per year for a public authority, savings of 80 kg CO_2 equivalents and around 16,000 liter of water could be achieved.

The regional authorities in Berlin consume about 620 million sheets per year. By consequently using eco-friendly paper made from recovered paper Berlin saves about 500 tons of CO_2 equivalents and nearly 100 million liter of water.

Street lighting

Regarding the illumination of streets and squares, huge saving potentials could be achieved, if the present gas and electric street lights would be replaced by energy efficient LED-lights. LED-Lights need less energy and they need less maintenance than gas or electric lights.

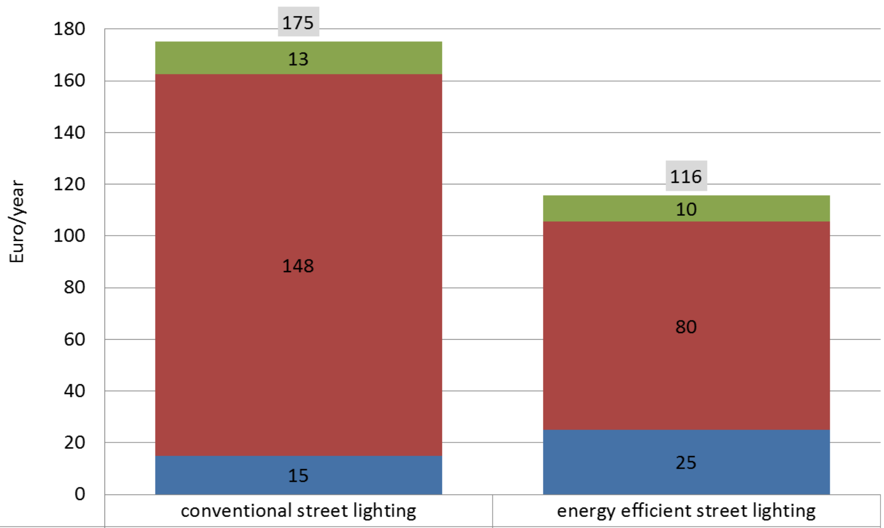
By purchasing LED-lights instead of conventional street lights (with high pressure sodium lamps) and by applying a brightness reduction during 6 hours of night time, 60 Euros could be saved each year per single street light (34%). Regarding the environmental impacts, 100 kg of CO_2 equivalents could be saved per street light (45%).

The following table illustrates the technical and economic product properties for a conventional and an energy efficient street lighting.

Table 1: Properties of a conventional and an energy efficient street lighting

Product properties	**Unit**	**Conventional street lighting**	**Energy efficient street lighting (LED)**
Single payment for acquisition			
Purchase price	€	200	400
Installation costs	€	100	100
Usage related costs			
Electrical power	W	80	60
Maintenance costs per maintenance interval	€	50	100
Maintenance intervals per year	A	4	10
Electrical power (brightness reduction)	W	80	30

[1]



	conventional street lighting	energy efficient street lighting
Life cycle costs	175	116
Annual maintenance costs	13	10
Annual energy costs	148	80
Annual acquisition costs	15	25

Figure 5: Annual life cycle costs of conventional and energy efficient street lighting per street light over a period of 20 years

The following figure illustrates the annual global warming potential (CO_2 equivalents) due to the energy consumption of conventional and energy-efficient street lighting.

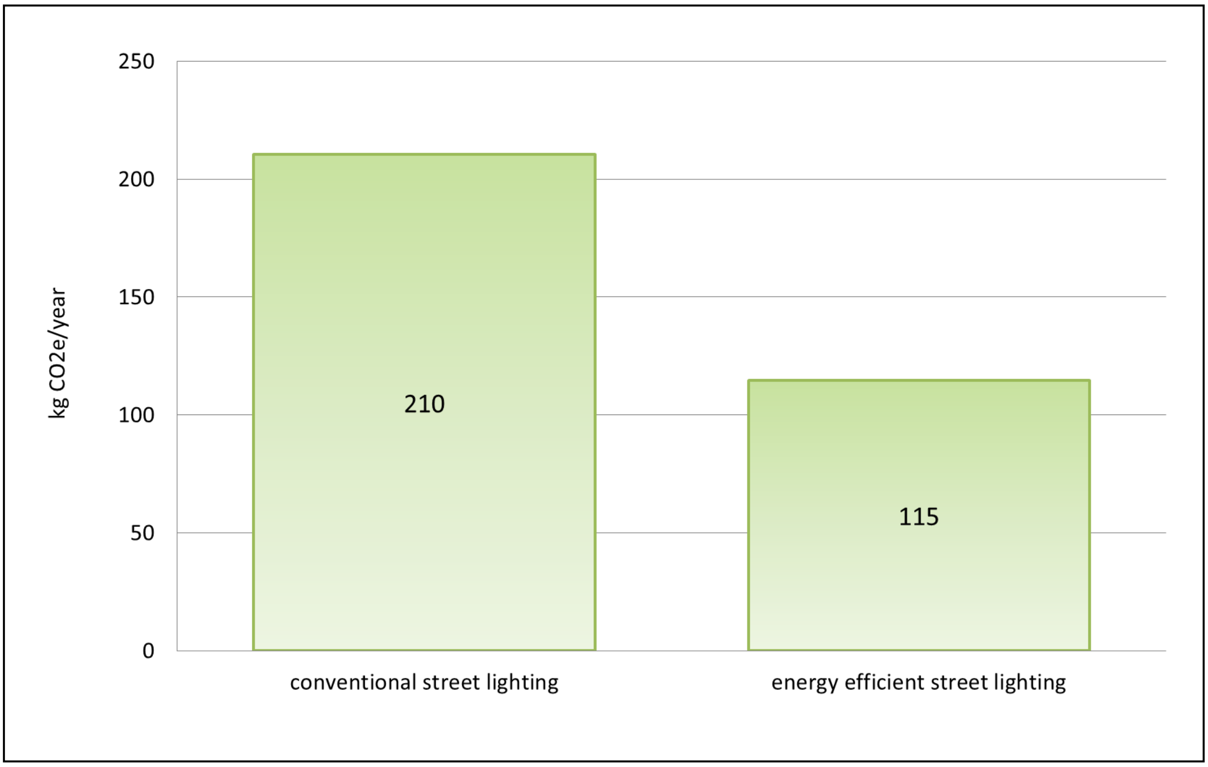


Figure 6: Annual global warming potential of conventional and energy efficient street lighting per street light due to the energy consumption

In average, each kilometer of street is equipped with 37 street lights. For 1,000 km street, more than 3,500 tons of CO_2 equivalents could be saved and more than 2 million Euros.

In Berlin there are 180,000 electric street lights. By retrofitting them with energy-efficient LED lamps 17,000 tons of CO_2 equivalents could be saved each year.

Conclusion

As shown in the previous chapters the use of environmentally-friendly products can make an active contribution to the reduction of greenhouse gas emissions. Besides that, the procurement of environmentally-friendly products also leads to economic advantages, like cost savings. There are lots of other products and services that are purchased by public procurement such as white goods, office lighting, vehicles, etc. Therefore, the entire savings potential of green public procurement is substantially, if public authorities consistently purchase environmentally-friendly products and services.

With the new regulation, that obliges the regional authorities in Berlin to take into account environmental impacts when procuring products and services with an acquisition value of 10.000 Euros and more, the city of Berlin makes an important step towards climate-friendly administrations.

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THE MDA (Major domestic appliances) EU ENERGY LABEL REACHING ITS LIMIT?

A DISCUSSION.

Norbert Herzog, International Key Account Manager MDA

GfK Retail and Technology GmbH

Abstract

The EU Energy Label has been a big success story and found imitators around the globe. Inefficient appliances have been discouraged, efficient appliances prevail. Nevertheless even the new EU Energy label layout seems to reach its limits as A+++ appliances are not a rareness in today's retail offers.

So we have come a long way and even the industry push for larger appliances with higher capacities was not able as of yet to beat the continuous path to more energy efficiency.

But how can future energy saving goals be achieved? Where are the biggest potentials for future energy savings? This paper takes a look at the current landscape of appliances sold on the EU market and the contribution of (fleet) energy consumption for different types of appliances to answer these questions.

Energy labelling for washing machines has clearly reached its limits, with A+++ becoming a standard offer in Western Europe. At a time when consumers decide between A+, A++ and A+++ offers, it is useful to better understand the actual differences in energy consumption / lifecycle costs for these appliances. Hence, the paper takes washing machines as a case study and takes a closer look at lifecycle costs, average prices and energy consumption for different energy label classes.

This provides a better understanding at how rational today's purchase decisions may be in terms of money savings for end-consumers.

Latest research results from GfK Retail and Technology are used in this paper to provide hard facts on those complex questions.

About GfK Point of Sales Tracking:

GfK has the world`s largest sample of tracked technical consumer product sales:

- With 425,000 retail point-of-sales and 770 reseller outlets report to us on a regular basis
- Capturing 14.5 million products from 760 product categories covering more than 120 distribution channels
- In 90+ countries globally
- Reporting on global standards enabling cross region comparability of sales insights

GfK provides insights into **what** products are selling, **when**, **where** and at **what price**. In terms of **energy efficiency** GfK tracks both energy label(s) as well as the stated energy and water consumption of appliances.

The world market of domestic white goods

Long-term growth path continues

GfK Retail and Technology estimates show consecutive world market growth until 2008, the year the financial crisis began. 2009 saw a downturn in sales of 5%. Most heavily affected countries besides Great Britain and Spain were the Central Eastern European economies and CIS[1] member states.

Since then, growth has stabilized with only one weak year in 2012, but global sales are forecasted to reach a new all-time-high of 186 bill. US$ in 2014.

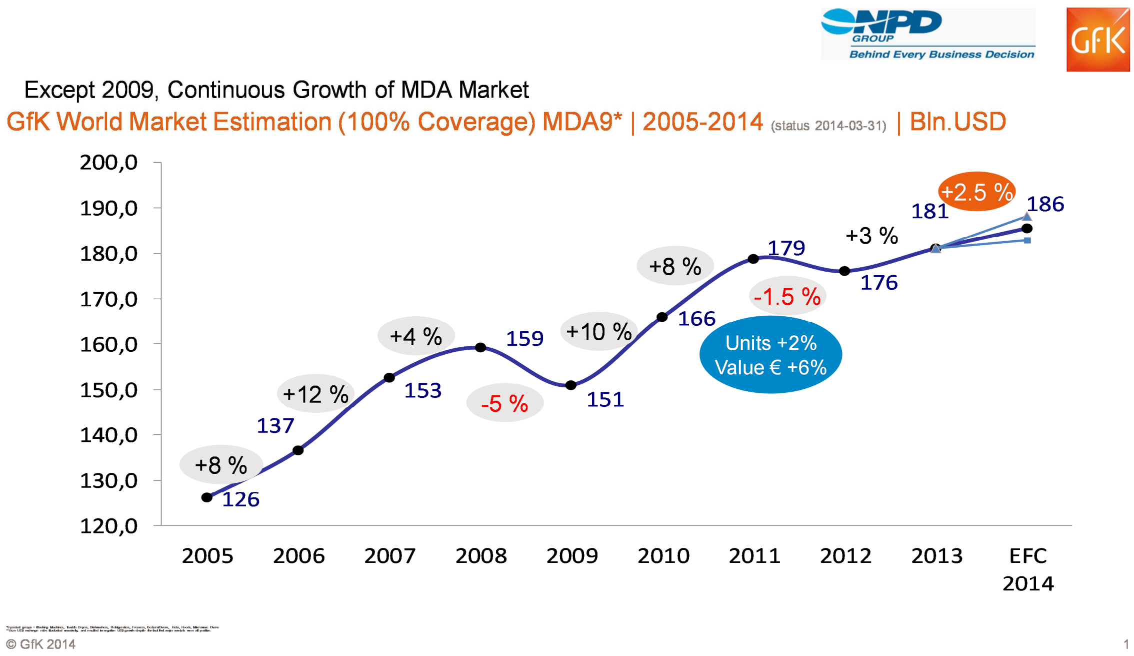

Figure 1: Global White Goods[2] market size and growth rates

Figure source: GfK Retail and Technology World Market Estimation

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[1] Commonwealth of Independent States, former Soviet Republics, including Russia, Ukraine, Kazakhstan

[2] MDA 9 includes: Washing Machines, Tumble Dryers, Dishwashers, Refrigerators, Freezers, Cookers/Ovens, Hobs, Hoods, Microwave Ovens

Europe is the most important market for domestic white goods

Western[3] and Central Eastern Europe (excl. CIS)[4] account for more than one quarter of the global market for white goods. The biggest single economy is China ahead of the United States. Given the stable sales shares of regions, only little change is to be expected for the coming year.

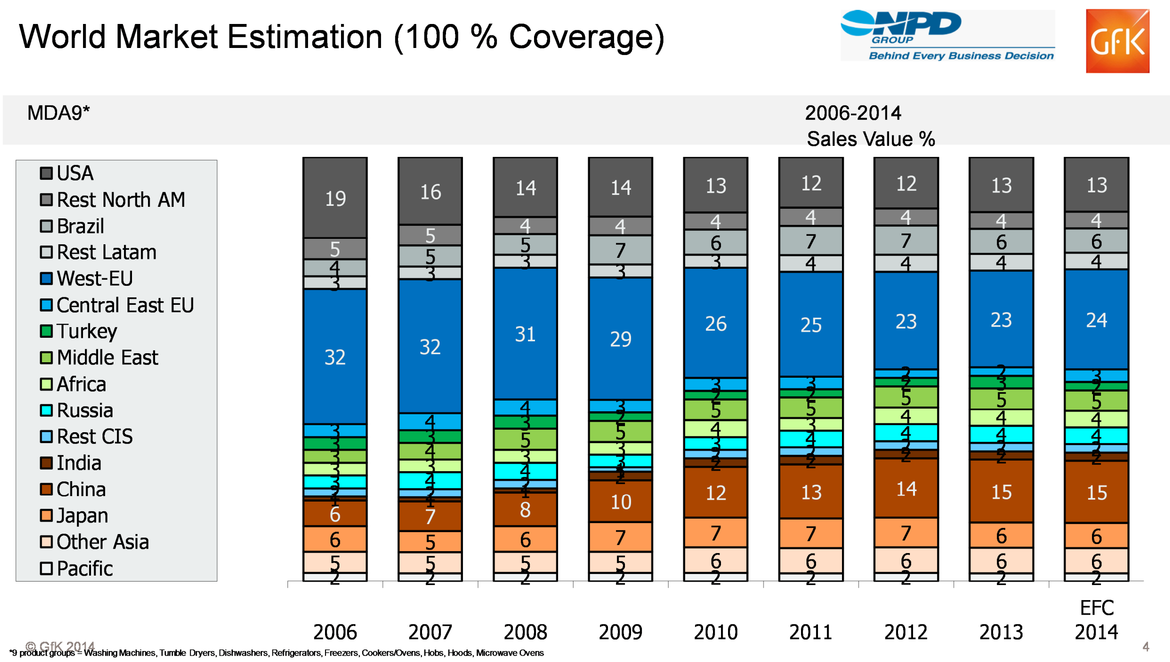

Figure 2: Global White Goods market by regions

Figure source: GfK Retail and Technology World Market Estimation

[3] Western Europe = 14 Western EU countries (AT, BE, DE, DK, ES, FI, FR, GB, GR, IE, IT, NL, PT, SE) + Luxemburg, Cyprus, Malta, Norway and Switzerland.

[4] Central Eastern Europe = 10 Eastern EU countries (CZ, SK, HU, PL, SI, RO, BG, EE, LV, LT) + Croatia, Serbia, Bosnia-Herzegovina, Kosovo, Montenegro, Mazedonia, Albania.

When relating these numbers to the overall number of households in these regions, it is remarkable that Western-Europe (~166m HH) clearly reveals the highest value share per HH, followed with some distance by Japan and the USA, while China has still significant potential to grow due to their high number of households.

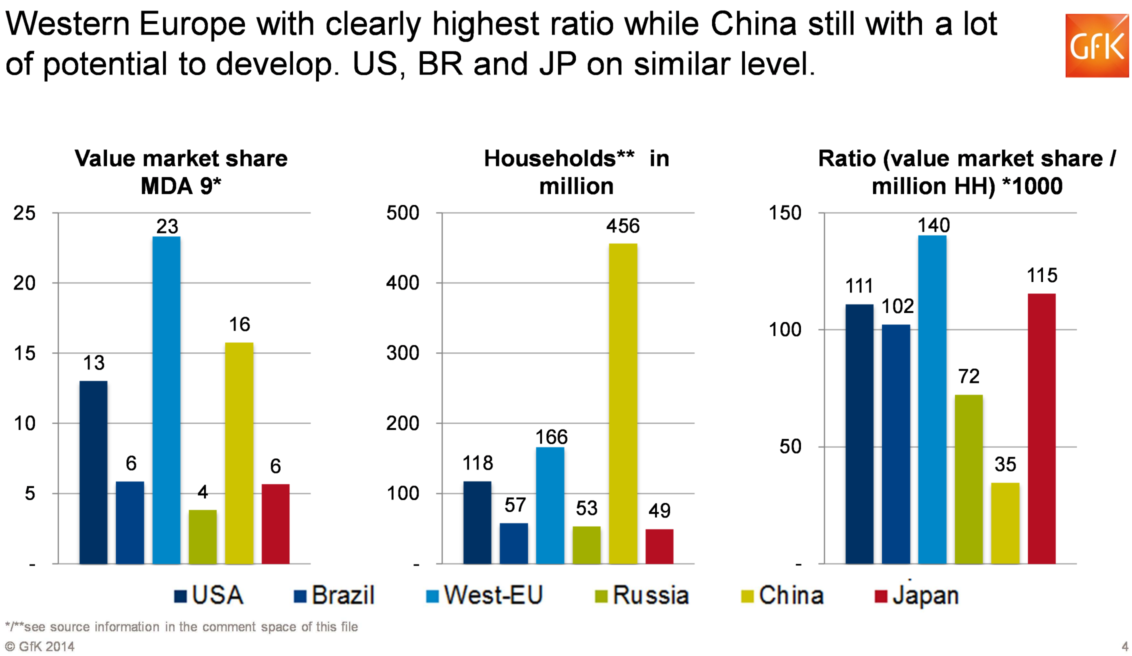

Figure 3: Global White Goods market by regions

*Figure source: GfK Retail and Technology World Market Estimation

**Sources HH sizes:

US: Principles and Recommendations for Population and Housing Censuses Revision 2, Department of Economic and Social Affairs, United Nations Statistics Division, 2008. Accessed on 2 October 2011.

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Average (declared) energy consumption of newly sold MDA (Major Domestic Appliances[5]) in Western Europe significantly reduced since 2010

MDA energy labels with intense development towards selling A+ to A+++ appliances

Sales of models in top energy label classes have increased steadily in the recent years: the market share of A+ or higher appliances jumped from 50% (2011) to 92% in 2014. This reflects the willingness of the industry to offer more and more energy efficient appliances and of consumers to buy them.

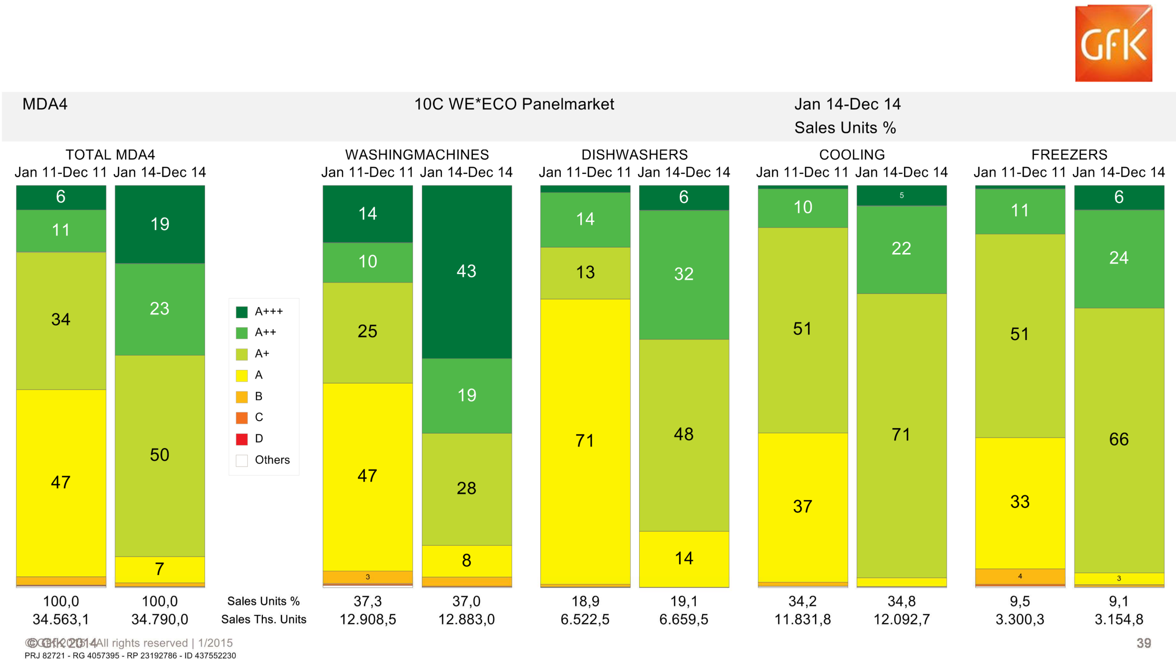

Figure 4: Market distribution by energy label classes by product groups (comparison 2011/2014)

Figure source: GfK Retail and Technology Retail Panel

Especially, the category of washing machines has potentially reached a limit in terms of energy label, as almost half of the sold washing machines have the best grade available (A+++). Already today, we can see manufacturers advertising A+++ minus 20%/40% or more.

Strong progress is also visible for dishwashers. While in 2011, the A class was the category with the highest share, today it is A+ and A++.

[5] MDA with energy label: washing machines, dishwasher, cooling, freezers and tumble dryers

Energy consumption reduction in Western Europe compensating the trend towards bigger appliances

The energy label classes are based on energy efficiency, but what about the actual average energy consumption of the appliances sold? The energy consumption index reported by GfK ECO reporting (extended reporting with details on energy related insights) provides a long-term overview, which is easy to interpret: in all product groups, the average energy consumption has been reduced; on average, it is 11% lower in 2014 compared to 2010[6].

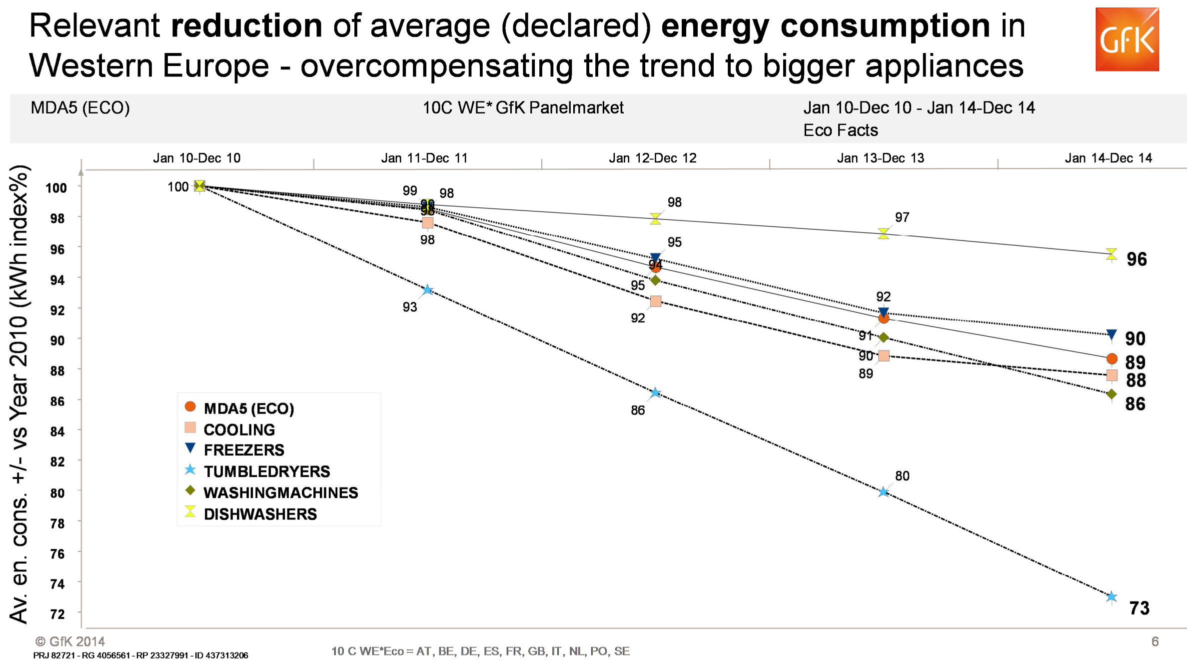

Figure 5: Energy consumption index by product groups (2010-2014)

Figure source: GfK Retail and Technology Retail Panel

These values take into account changes in average size or capacity of appliances, especially the growth in the past years.

While in 2009, a capacity of 5 or 6kg was standard for washing machines; today consumers clearly turn towards purchasing models with a capacity of 7kg or more. The arguments of more flexibility and fewer washing cycles seem relevant to them. On the other hand, the market offers more and more washing machines with greater capacity which limits consumers' choices for smaller capacities.

From the industry side, a trend for larger appliances is also welcome – generally meaning higher prices/revenues and the possibility to reach higher energy label classes with higher capacities (scaling effects).

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[6] Calculation of energy consumption (kWh) is an approximation based on declared annual energy consumption. If needed (due to different label declarations), energy consumption per cycle has been converted to annual energy consumption using declared cycle energy consumption and average cycles per year information. Although some inherent lack of comparability of declared energy consumptions across different labels remains, this was found to be the best possible method to make developments comparable.

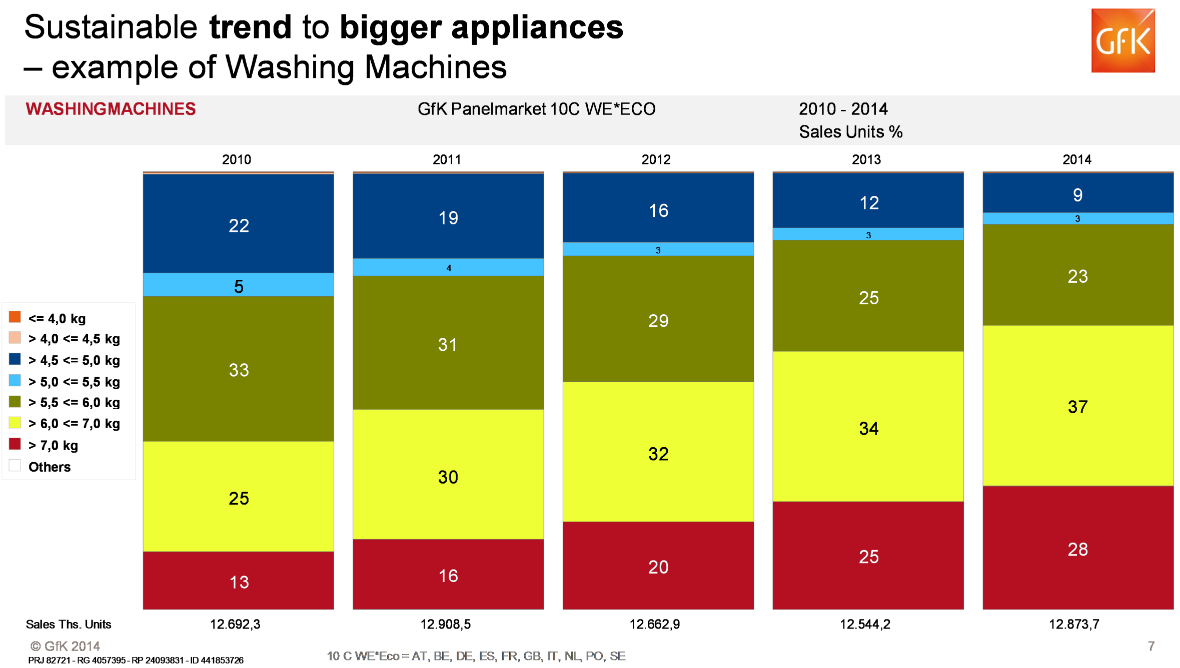


Figure 6: Development of capacity of washing machines (2009-2014)

Figure source: GfK Retail and Technology Retail Panel

When excluding the influence of capacity growth and looking at the average energy consumption of sold washing machines **per rated kg,** the impact of pure (declared) energy efficiency improvements is revealed. It demonstrates a significant reduction of one to one comparable energy consumption of 25 % in the past 5 years (2014 vs. 2010).

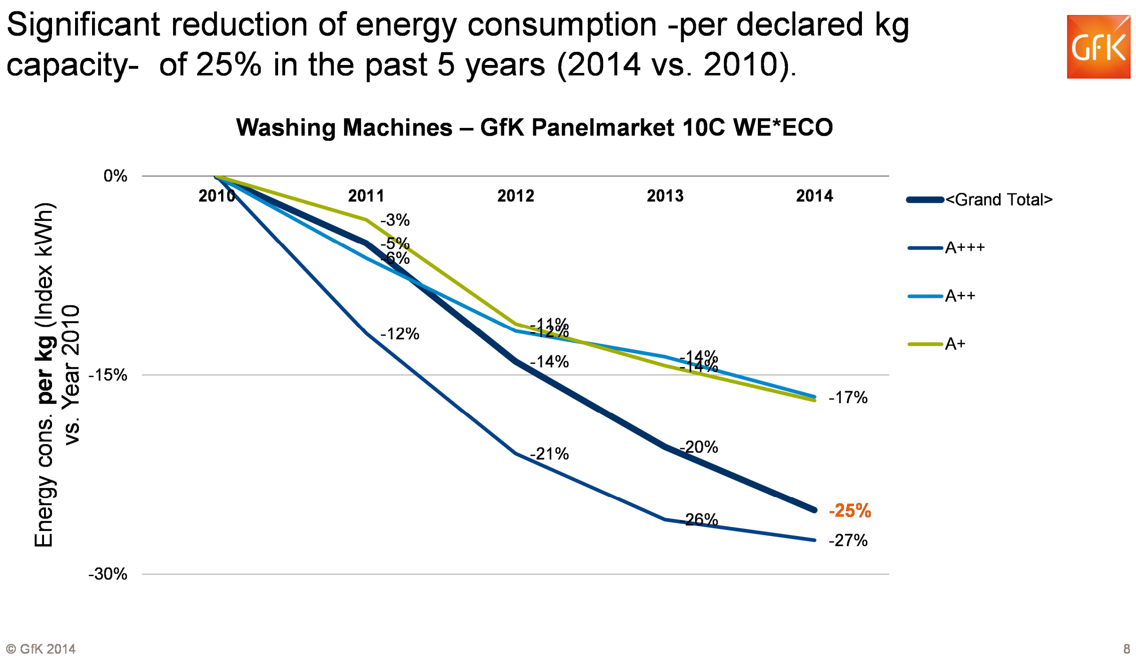


Figure 7: Energy consumption per kg (Index kWh) vs. Year 2010

Figure source: GfK Retail and Technology Retail panel

Respective contributions to energy savings

To assess the actual impact of these trends on total fleet energy consumption[7], it is necessary to remember that the total energy consumption of a product group depends not only on the average consumption per appliance, but also on the number of appliances sold/in use.

“Must have” appliances, such as washing machines and refrigerators are now regularly purchased by nearly all EU families, while “nice to have” appliances like tumble dryers and dishwashers consume less energy overall, simply because fewer appliances are sold due to lower household penetration or longer lifetimes.

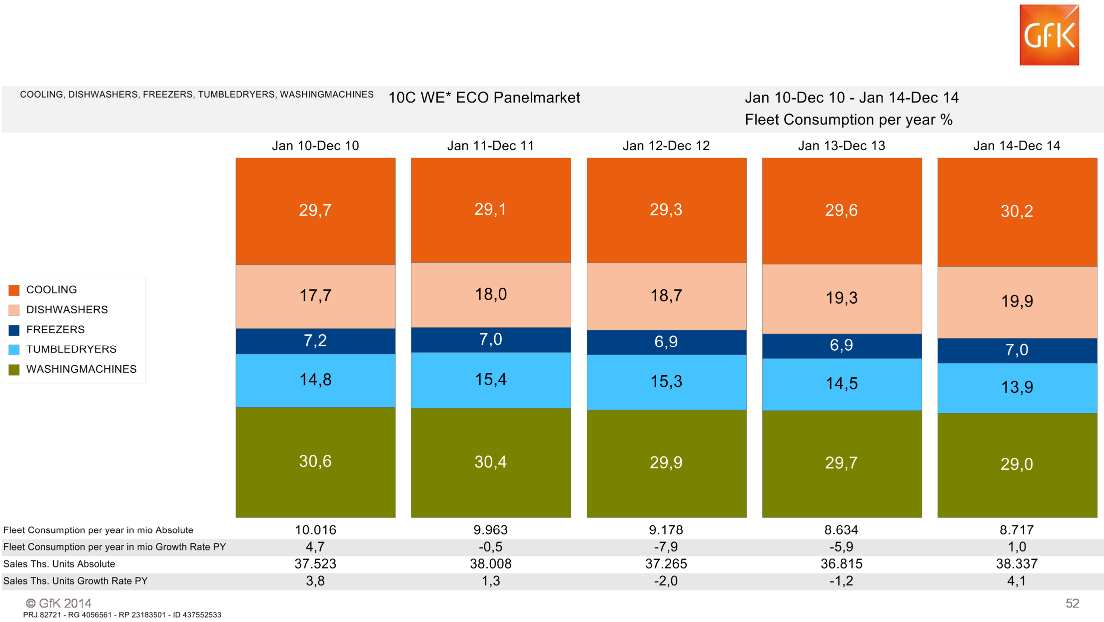


Figure 6: Share of fleet energy consumption by product groups (Sum of the energy consumption of all sold appliances) **(2010-2014)**

Figure source: GfK Retail and Technology Retail Panel

The shares of fleet consumption by product category have not changed dramatically across the years. This reflects the fact that sales levels are relatively constant in saturated markets. But there are subtle differences in the energy efficiency progress achieved across the product categories (for more details, also refer to Figure 7).

When looking at the five major product groups in Figure 6, the biggest share of energy consumed in EU households can be allocated to washing machines and refrigerators – the “must have” appliances with highest household penetration.

When looking at the **average** energy consumption per product type, the picture is different. The energy intensiveness of tumble dryers and dishwashers stands out. Through innovative heat pump technology, especially in the area of tumble dryers, significant energy efficiency potential was exploited and average energy consumption was reduced dramatically since 2010. This could also be a success of the energy label, as only heat pump driers can get an A+ (or higher) label.

[7] Sum of energy consumption of all sold appliances

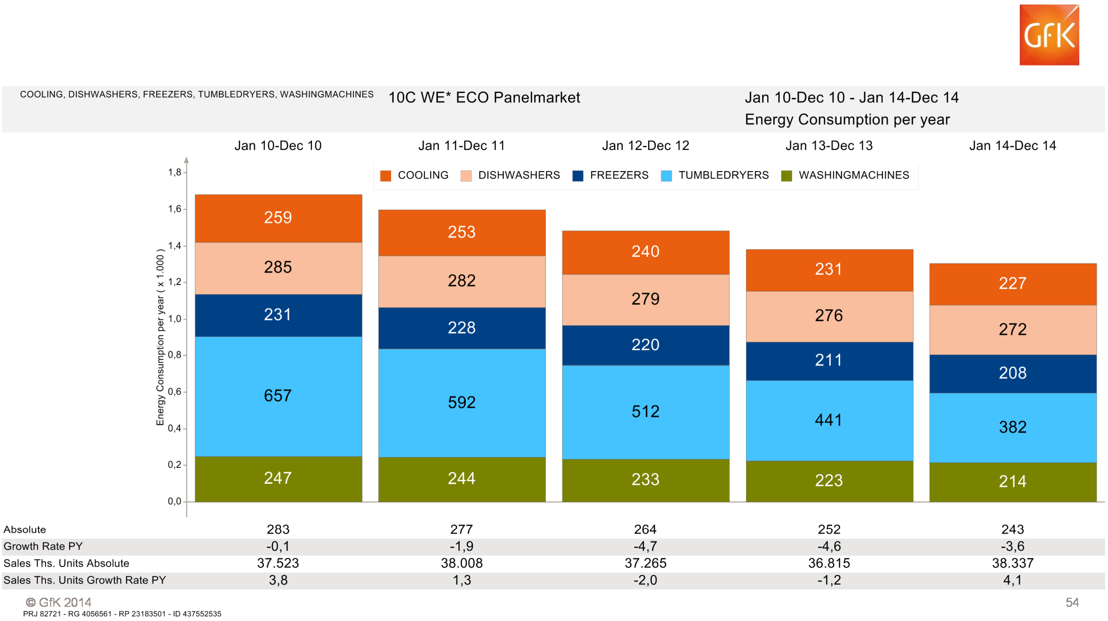


Figure 7: Average energy consumption (declared kwh/year) of sales per product group (2010-2014)

Figure source: GfK Retail and Technology Retail Panel

Where are future energy efficiency potentials?

Dishwashers

Dishwashers are relevant as their average unitary energy consumption is still relatively high and fleet consumption has a share of 20%. Even more important could be the fact that the penetration of more energy efficient products in the recent years has been clearly smaller compared to the other product groups. Sold dishwashers only reduced their average energy consumption by 5% compared to 2010.

If a development for dishwashers had been achieved as for washing machines (reduction of energy consumption of more than 13%), a potential of approx. 167 million kWh[8] could have been saved in 2014 on newly sold dishwashers across the largest 10 European countries.

In terms of energy labelling shares, A+++ dishwashers are still uncommon, but only classes above A can be sold. Hence, the differentiation for consumers is relatively low at the moment.

Refrigerators and washing machines

Technically, the highest potentials clearly lie with refrigerators and washing machines, as they are together responsible for almost 60% of the fleet consumption vs. 40% for dishwashers, freezers and tumble dryers. Another factor contributing to the relevance of washing machines is the fact that they do not only use electricity, but also water (and consumption of both is very closely connected).

As a reduction of one kWh on average annual energy consumption in the washing machine category has more than a two-fold impact compared to tumble dryers or even more than a three-fold impact compared to freezers, it is important to ensure that energy efficiency progress continues to be politically stimulated in this product category through (new) energy label decisions. The current label has reached its limit and there is a clear need to encourage and reward new innovations.

[8] Source: GfK Retail and Technology – own calculation

This could be done range from warm water access from solar panels to more effective motors, etc. To make this relevant for all market stakeholders, an effective energy label needs to be available for industry and comprehensible for consumers.

Political processes to revise labeling directives / regulations are on-going.

More than 50% of washing machines sold are now A+++

Within the past five years, the energy label distribution of sold washing machines shifted completely. While in 2010 the majority of washing machines was labelled A, already two years later A+++ was the most important value segment. Today, more than half of washing machines are labelled A+++ when sold to consumers (Note: Relabeling and changes in energy efficiency calculation also had an impact on selling higher labelled products. If products were relabeled after introducing higher label values these are shown within the higher label in any period.).

Obviously, the trend towards the most efficient segment continues and consumers are still ready to purchase higher label classes. Still, there is currently a natural limit reached as no next energy label step can be made under the current layout. As with the old energy labels, some manufacturers have started introducing A+++ -20%/40%, etc. into the market to promote new “super-efficient” appliances.

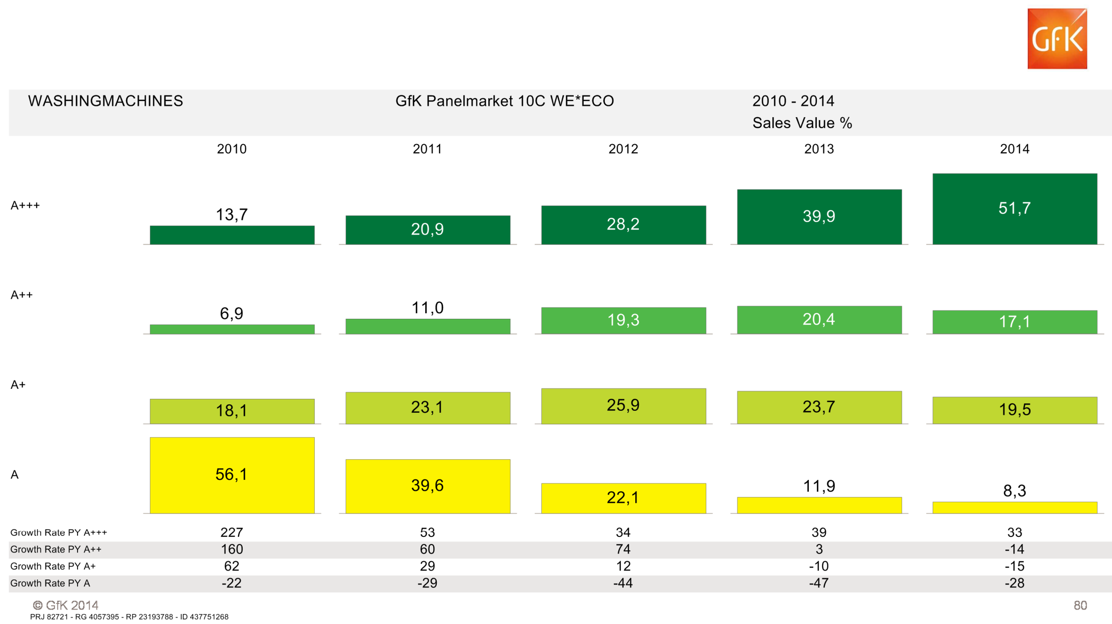


Figure 8: Sales value shares by energy label class (2010-2014)

Figure source: GfK Retail and Technology Retail Panel

Further energy savings despite trend towards higher loading capacities

Energy efficiency is also increasing within energy label segments, i.e. A+++ washing machines in 2010 needed with 31 kwh/kg 39% more energy/kg than in 2014 (see figure 9). For sure increased capacity had an influence on this development but inherent efficiency increases are significant as well → 21% less “inherent” (not per kg but overall in A+++) energy consumption 2014 vs. 2010 (see figure 10).

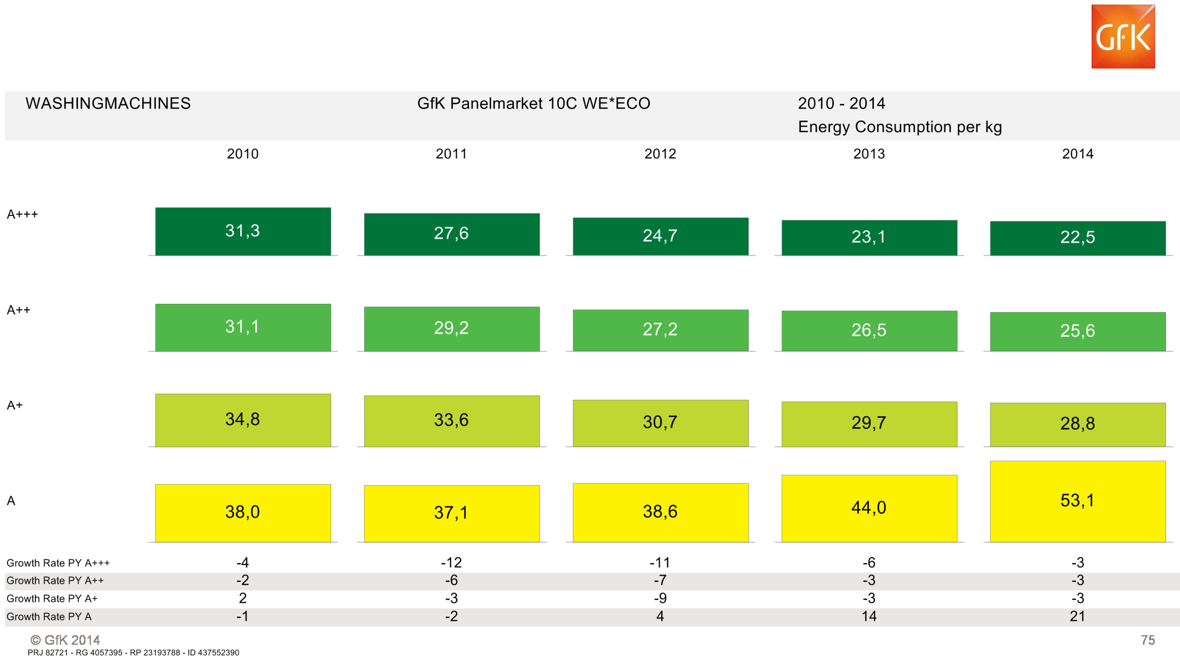


Figure 9: Average annual energy consumption per kg by energy label class (2010-2014)

Figure source: GfK Retail and Technology Retail Panel

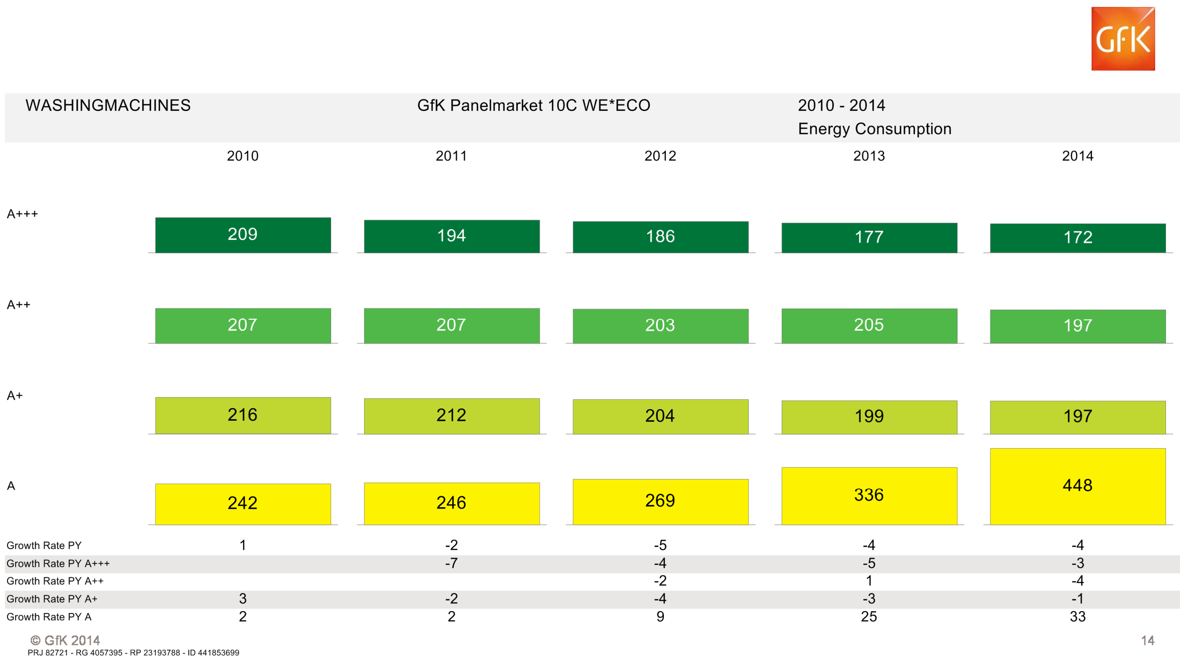


Figure 10: Average annual energy consumption by energy label class (2010-2014)

Figure source: GfK Retail and Technology Retail Panel

Assuming the same reduction in declared energy consumption in the next five years as in the past five years, another 373 Mio kWh/year could be saved on sold products in the year 2019 compared to 2014. Hence, stimulating and rewarding further innovation with more adequate energy labels would have a big impact on household energy consumption in the future.

Case study on washing machines: what actual difference does the energy label make in financial terms?

Energy costs are almost equal while cost of appliances are making the difference

Looking deeper into the running costs of appliances over time, energy/water should play an important role as it is one of the main arguments when selling more efficient and expensive appliances.

On a per rated kg perspective it becomes clear that average energy/water costs are very similar for A+ to A+++ washing machines. So rationally for consumers there is little financial benefit, in fact due to higher average purchase price of A+++ appliances, the lifecycle costs even turn out higher for A+++.

Consumers do not have this cost transparency and for sure other arguments like sustainability have become more relevant, but it shows that the pure ROI (return on investment) argument may not be sufficient in the future to spark demand for even more efficient washing machines.

Additional savings in energy may not be fully compensated financially, particularly in times of potentially stagnating energy costs the consumer demand can drop.

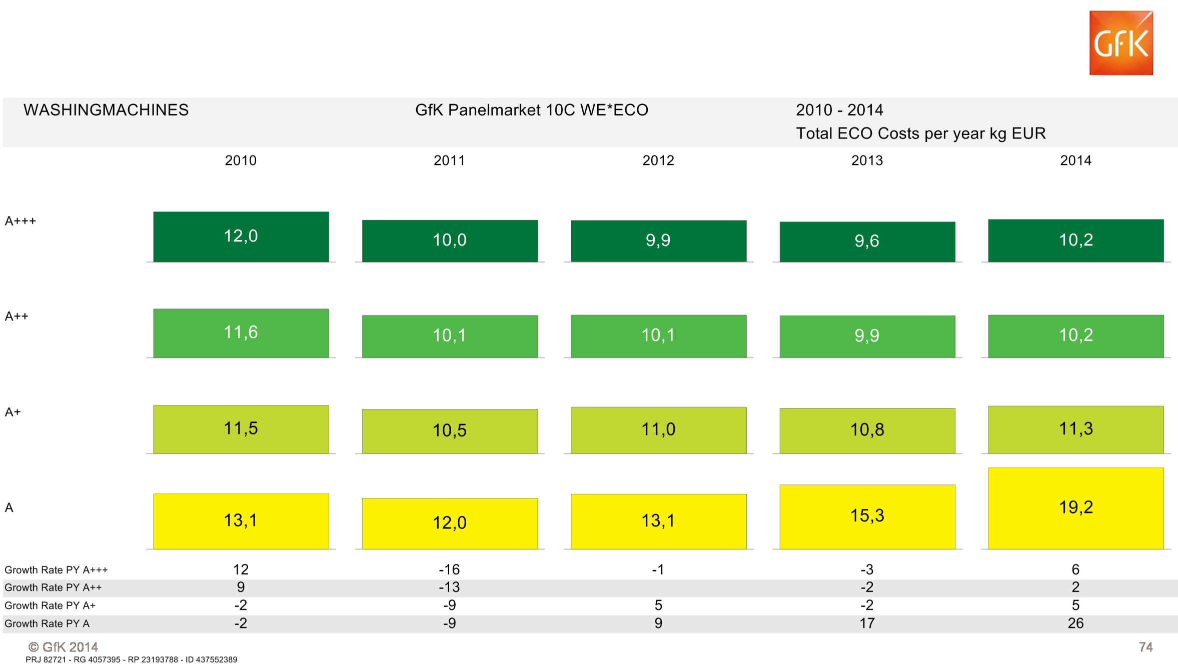


Figure 11: Annual energy/water costs[9] per declared kg by energy label class (2010-2014)

Figure source: GfK Retail and Technology Retail Panel

[9] Source if electricity and water costs: Europe's energy portal and GfK data. Costs are updated once a year.

For lifecycle costs, the most current costs are used for calculation, flat price development for future years is assumed in calculations.

Lifecycle cost benefit for A++/+++ cannot be demonstrated

When combining average initial purchase costs and energy/water running costs over a life cycle of 12 years, already today no financial benefit of A++ or A+++ can be demonstrated.

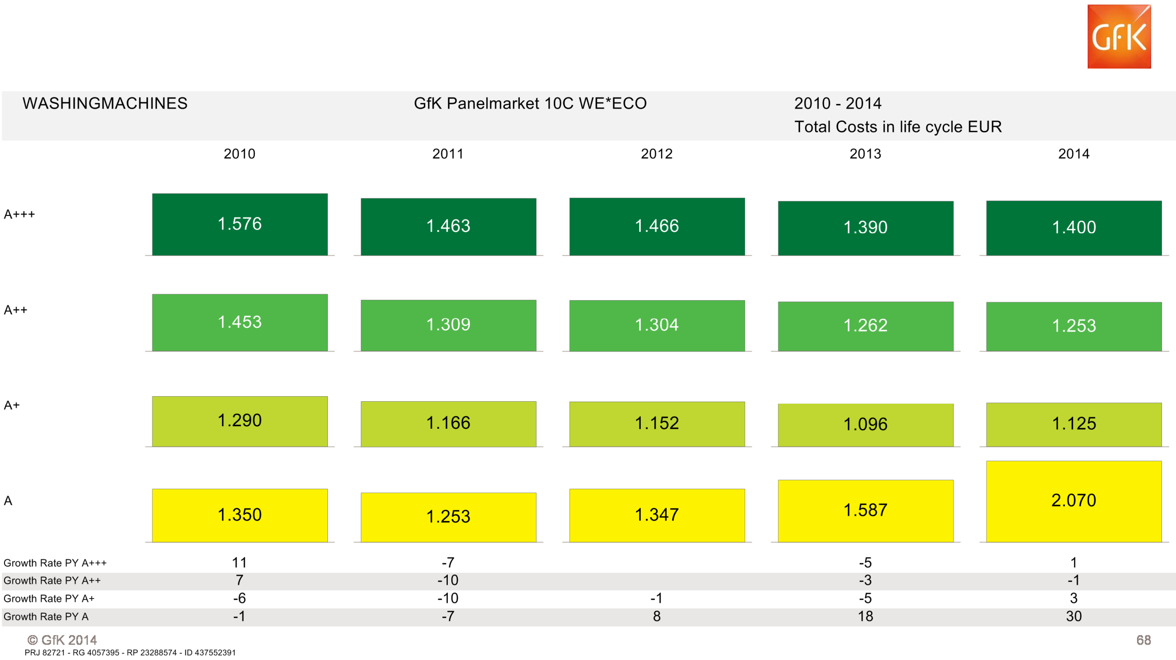


Figure 12: Lifecycle costs by energy label class (2010-2014)

Figure source: GfK Retail and Technology Retail Panel

To exclude the potential effect caused by calculating the average of very different models the analysis was performed with similar models, in this case 7kg models (see figure 13). In this more homogeneous analysis the result is very similar to the results described in figure 12.

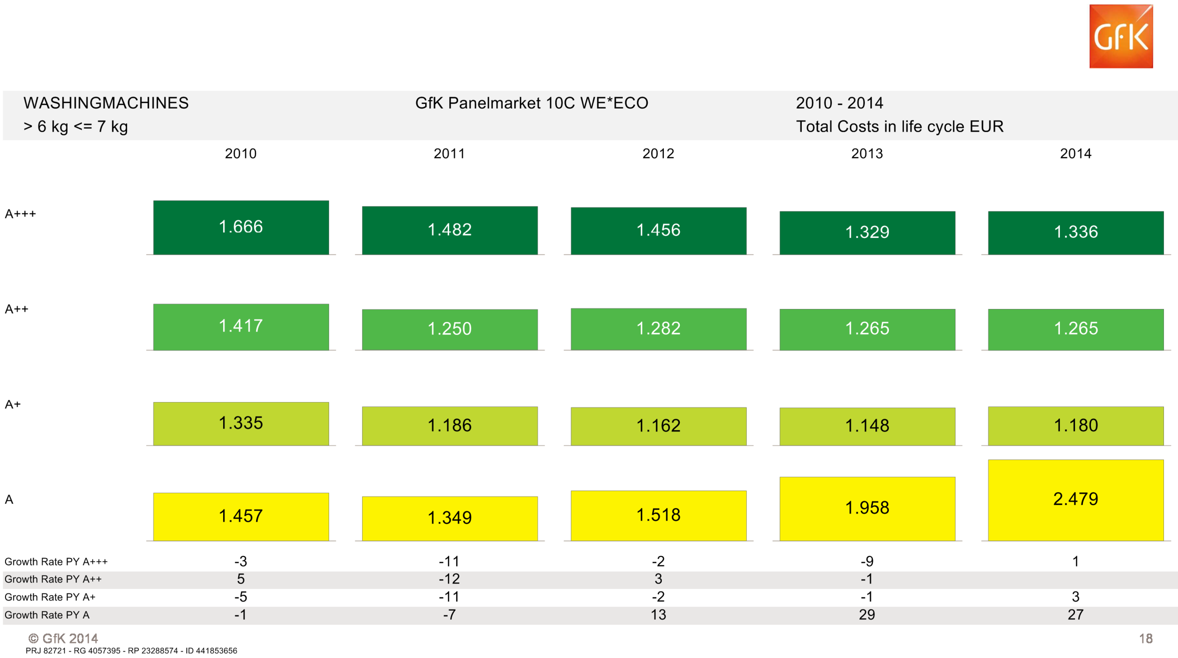
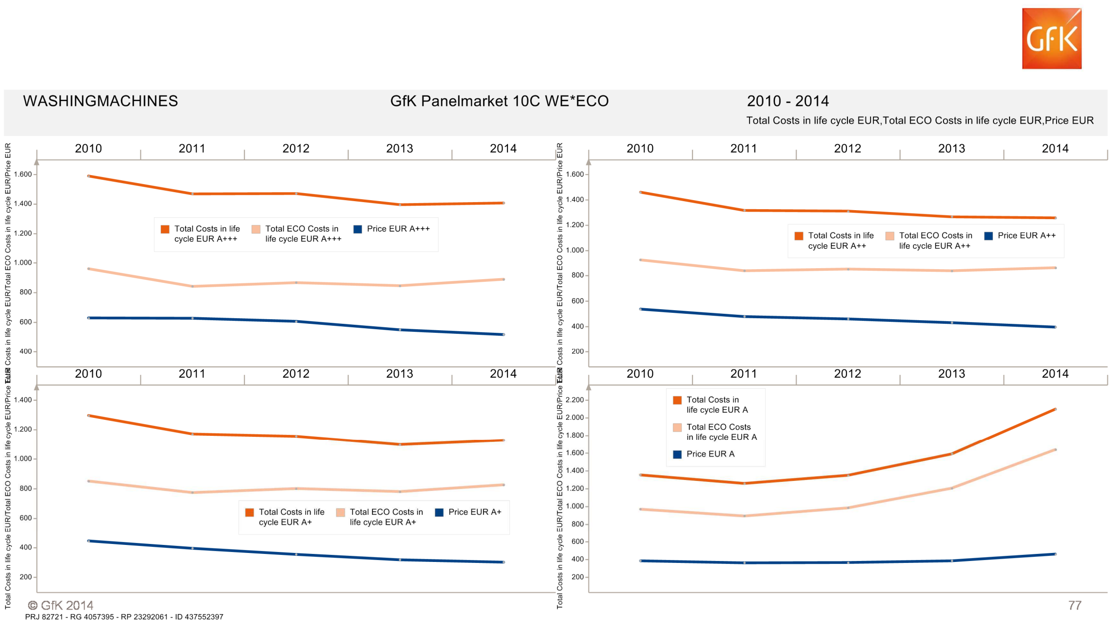


Figure 13: Lifecycle costs of 7kg models by energy label class (2010-2014)

Figure source: GfK Retail and Technology Retail Panel

The lower average initial price of A+ appliances makes the difference, although we should keep in mind that more expensive washing machines in A++ and A+++ classes are possibly equipped with multiple additional features besides a better energy efficiency (e.g. automatic dosage, inverter motor, etc) which in the eyes of consumers may justify the increased costs.



Conclusion

There have been massive steps forward in the past years towards higher energy labels sold in the MDA markets. It was also proven that this development had a considerable effect on the average declared energy consumption of appliances.

This means that he differentiating power of the EU energy label has been significant, but varying by product group. For washing machines, the A+++ label has already become a standard (in Western Europe) which lead too superdeclarations and a lack of differentiation by consumers. This suggests that the energy label has already now reached its limits and most other categories will face this situation in the near future as well.

Once energy labels are not differentiating any more, focus may move to actual cost savings. For washing machines it was demonstrated that the additional costs involved for higher energy efficiency classed cannot be made up by decreased energy consumption costs in the lifecycle. This is likely to hold true for superdeclarations as well.

Future potentials for energy savings remain with refrigerators and washing machines as these are the appliances with the highest share of fleet consumption[10] (about 60% of sales weighted energy consumption). In addition, dishwashers may present an opportunity as energy efficiency gains in the past have been more moderate vs. other product groups.

To stimulate enhanced energy efficiency, new label requirements should be implemented just before differentiating power of old specifications is lost. Hence a sophisticated market monitoring is recommended to align potential timing of implementation processes in the future – and new label requirements should be set based on proper understanding of market dynamics to avoid frequent relabeling.

[10] Sum of energy consumption of all sold appliances

Leapfrogging developing country markets to energy efficient lighting, appliances, and equipment

Patrick Blake, United Nations Environment Programme

Steve Kukoda, International Copper Association, Ltd.

Abstract

The United Nations Environment Programme (UNEP), United Nations Development Programme (UNDP), the Global Environment Facility (GEF), CLASP, the Natural Resource Defense Council (NRDC), and the International Copper Association (ICA) have recently formed a public-private partnership (PPP) to reduce global electricity consumption by 10 percent. The partnership was formed under the framework of the UN Secretary-General's Sustainable Energy For All (SE4ALL) initiative and the Energy Efficiency Accelerator Platform. By transforming markets to energy efficient products, including lighting, appliances, and equipment, an immense amount of financial and environmental wealth could be saved, allowing for improved livelihoods throughout the world. Through this market transformation over 2,500 TWh of electricity could be saved, which would result in CO_2 savings equivalent to the emissions of 500 million cars. The partners of the initiative bring their collective experience; expertise and know-how to support countries in making these goals become reality.

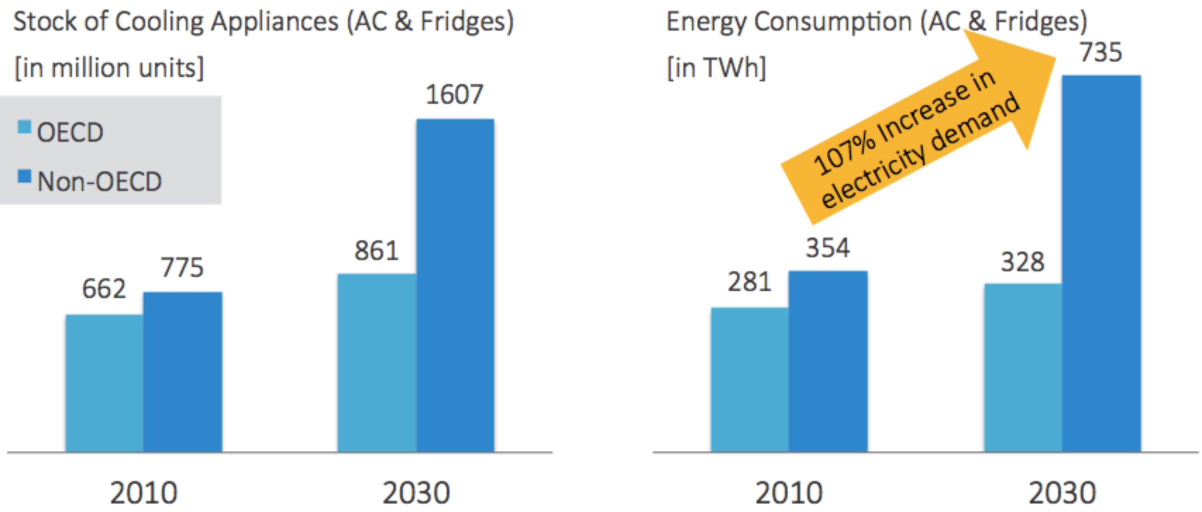
Introduction

Energy provides large opportunities for developing-country populations, including economic development and greater productivity to allow for increased educational and business prospects. However, the greenhouse gas emissions of fossil fuel energy production also contributes greatly to global climate change, which will have an even larger impact as populations in developing and emerging countries increase their future consumption in areas such as lighting, appliances, and equipment. These countries, in effect, will be given the option in the coming years to choose a path to transform their markets to high-efficiency products providing energy, financial, and environmental benefits; or, a path of inefficient products causing a strain on the population, economy, environment and government.

Exponential growth of lighting, appliances, and equipment

Over the next ten to twenty years, developing and emerging countries will undergo massive growth in the stock of domestic appliances as populations grow, incomes rise and an increasing number of people move to urban areas. Without the implementation of appropriate policies, the growth in stock will result in a great strain on the global environment, electricity infrastructure and ultimately hinder further economic growth. As is shown in Figure 1, energy demand for refrigeration is expected to grow by over 100% in non-OECD countries, with some countries such as India demanding six times more energy for refrigeration compared to today.

Figure 1. Projected growth of air conditioners and refrigerators between 2010 and 2030

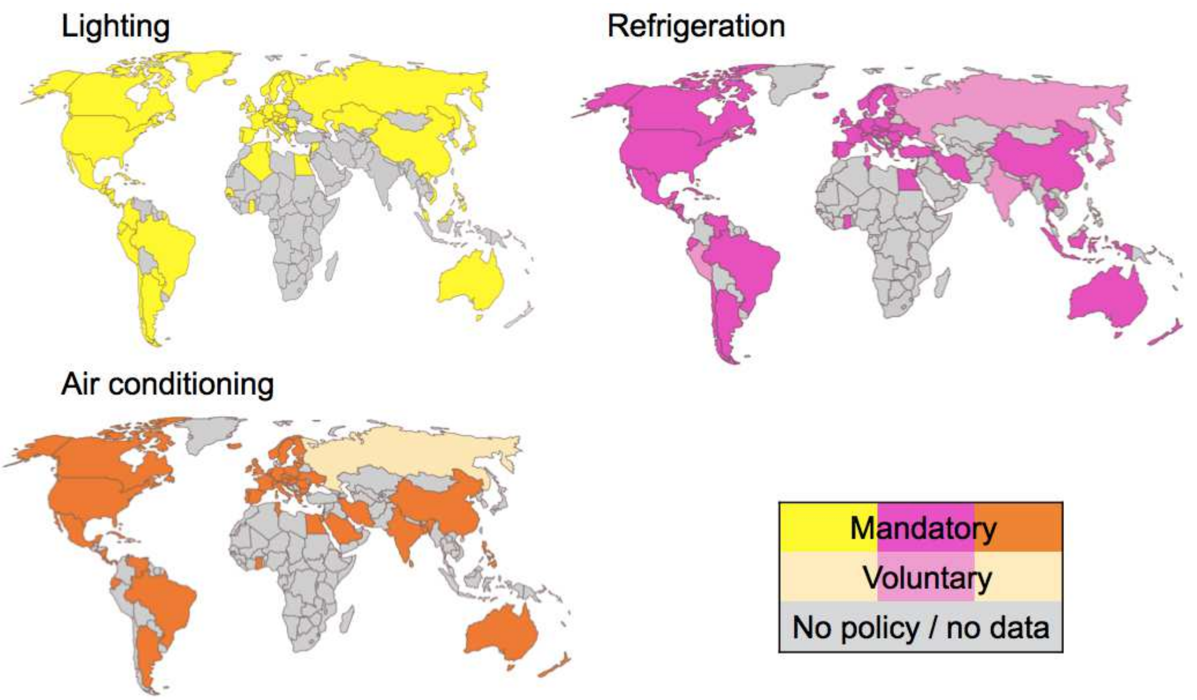


Source: UNEP, 2014c

Status of policies in developing country markets

While most OECD member countries have already established an integrated policy approach, including regulatory mechanisms and supporting policies, most non-OECD do not have a policy in place for the priority lighting, appliance, and equipment technologies. This divide is shown in Figure 2, where very large parts of Africa, Asia, Latin America, and island nations lack minimum energy performance standards (MEPS) for the highest-energy- consuming products of lighting, refrigerators, and air conditioners.

Figure 2. Global status of minimum energy performance standards for lighting, refrigeration, and air conditioners



Sources: Harrington, 2014 and CLASP S&L Database.

Further, a large number of the non-OECD country norms and standards have become obsolete, since efficiency levels have not been updated following technology advancements. For instance, refrigerator labels in Argentina and the Philippines have not been updated since 1997 and 2000, respectively. [CLASP S&L Database, 2014]

The effect of such standards being 10 or 15 years out of date could be estimated by studying the rate of improvement in the United States market shown in two successive periods of 10/11 years (1980 to 1990 and 1990 to 2001), where annual consumption reduced by 30%, and then again by 30%. Therefore, it is possible to conclude that standards that were set 10 or 15 years ago may be failing to achieve savings of between 30% and 45% in annual consumption when compared with appliances under newly revised standards. [UNEP, 2014c]

Global partnership to support countries in the transformation

Since 2010, UNEP and Global Environment Facility (GEF) en.lighten initiative has supported governments and regional integration bodies to develop policies, strategies and actions for the phase-out of inefficient lighting products. It provides technical and methodological support in the design and completion of National and Regional Efficient Lighting Strategies, effectively helping countries moving to high-performance technologies in 2014.

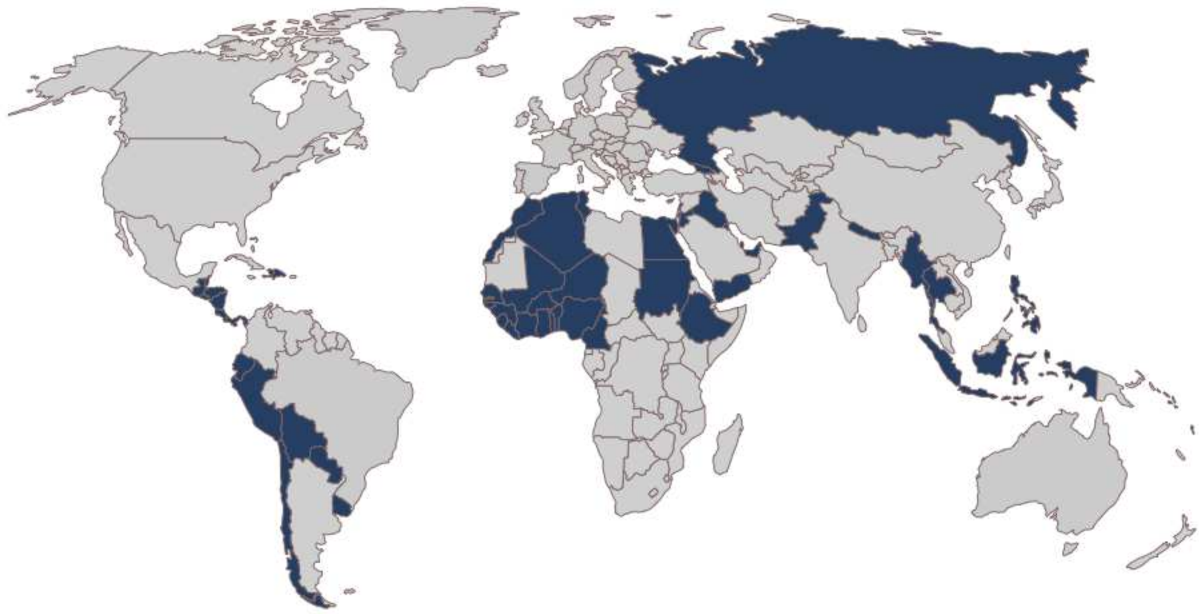
Based on the successful approach of the en.lighten initiative and as part of the SE4ALL Accelerator Platform, UNEP, UNDP, the International Copper Association (ICA), CLASP, the Natural Resources Defense Council (NRDC) and the GEF, launched the Efficient Appliances and Equipment Global Partnership Program (working title). This global partnership provides tailored assistance to governments to develop and implement national and regional policy and demonstration actions to facilitate the permanent transition to energy-efficient appliances and equipment. Through the partnership, UNEP's support to countries expands from lighting products to the next high-impact opportunity products including refrigerators; air conditioners; fans; electric motors; distribution transformers; and information and communication technology (ICT, primarily televisions).

In addition to combining the strength of international organizations and leading like-minded organizations, the partnership also includes leading private sector manufacturers, such as ABB, Acerlik, Electrolux, Mabe, Philips Osram, and many more expected to join in the near future. The global partnership is part of the SE4ALL Accelerator Platform and delivers on the Accelerator for Efficient Appliances & Equipment, in support of the SE4ALL initiative's goal of doubling the rate of improvement in energy efficiency globally.

The strength of this public-private partnership serves to mobilize private sector resources, (technical, managerial and financial) to help governments achieve and deliver a transition to energy-efficient lighting. By forming a public-private partnership, the initiative can support the establishment of regulatory and institutional frameworks, build technical capacity among policymakers and bring more innovative and energy-efficient lighting, appliance, and equipment technologies into the mass market. Further, the private sector can play an important role in communicating the benefits of efficient products to consumers through consumer-awareness campaigns, demonstration projects, and distribution campaigns.

Through both initiatives, sixty-six developing and emerging countries have joined the global partnership (Figure 3) to advance their economies to energy-efficient lighting, appliances, and/or equipment.

Figure 3. Countries pledging to advance their economy to energy efficient lighting, appliances, and/or equipment (as of March 2015)



Integrated policy approach

The global partnership supports countries to put in place actions that will permanently leapfrog markets to high-efficiency products, using a flexible *integrated policy approach*, which is adapted to the uniqueness of each appliance and equipment type. Included in the integrated policy approach are:

- **Minimum energy performance standards (MEPS),** comprising of performance, quality requirements, and test methods to ensure the efficiency and quality of products available in the market;
- **Supporting policies** to restrict the supply of inefficient appliances and equipment and **financing packages** to overcome the first-cost-barriers and promote the demand of MEPS-compliant products in impoverished sectors of society;
- **Monitoring, verification and enforcement** to discourage the distribution of non-compliant products;
- **Environmentally sound management** to safeguard the environment and human health throughout the product lifetime, with particular attention to ozone-depleting substances in obsolete equipment that significantly contribute to greenhouse warming.

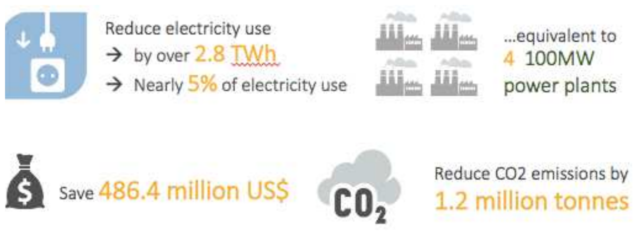
National and regional strategies for energy-efficient products

After a country or region commits to advancing their markets to energy-efficient lighting, appliances, and equipment, the partnership works with country representatives to develop a national or regional strategy for energy-efficient products. The purpose of a national strategy is to focus priorities by developing a common vision and goals on transforming the market to energy-efficient

In Focus: Strategy for Energy Efficient Lighting in Chile

- Chile adopted a national efficient lighting strategy in late 2013, phasing-out inefficient incandescent lamps through an integrated policy approach, which was supported with technical expertise and financial support of UNEP.
- The national strategy resulted in a follow-up GEF national project to advance higher efficient lighting (including mass deployment of LEDs) and surveillance capacities to ensure product compliance.

Expected annual savings for Chile are:



products. The strategy will define the scope of products based on an assessment of electricity demand and electricity usage, as well as anticipated consumer trends. The strategy will set national objectives and a detailed roadmap based on the integrated policy approach for each individual product, or groups of products. Such efforts will ensure a coherent strategy, which will save time, effort and resources, and provide a systematic and holistic plan to ensure the successful transition to energy efficient appliances, equipment, and lighting. [UNEP, 2013]

UNEP has already supported 27 countries to successfully develop National and Regional Efficient Lighting Strategies, including in Central America (8 countries - Belize, Costa Rica, Dominican Republic, El Salvador, Guatemala, Honduras, Nicaragua and Panama), Economic Community of West Africa States (15 countries - Benin, Burkina Faso, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo), Tunisia, Chile, Jordan, and Uruguay.

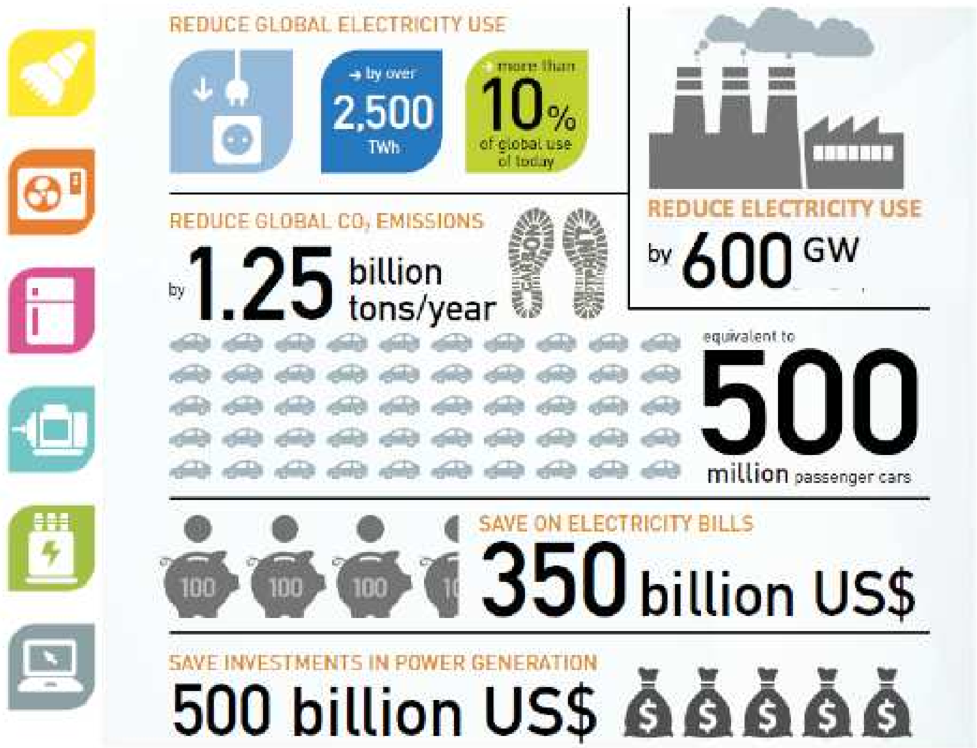
Additionally, UNEP is currently collaborating with the Secretariat of the Pacific Community and its twenty-two member countries to develop a Regional Efficient Lighting Strategy with an expected launch in 2015.

Benefits from leapfrogging markets to energy efficient products

Energy efficiency is one of the fastest and most affordable practices to mitigate climate change, prevent excess demand of electricity, avoid electricity rationing (blackouts), reduce the investment in power generation, and reduce the cost of energy subsidies. Further, the use of efficient appliances and equipment provides savings at country and citizen levels in financial, environmental and energy terms. These reduce the value of electricity bills as well as imports of fossil fuels, improve consumer welfare and reduce carbon dioxide emissions.

The projected savings from a transition to energy efficient lighting, appliances, and equipment are estimated to be 2,500 TWh (Figure 4), which would save consumers US$ 350 billion on electricity bills and be equivalent to reducing electricity capacity by 600 GW. Further, CO_2 emissions would be reduced by almost 1.25 billion tonnes each year, which is equivalent to taking 500 million passenger cars off the road. [UNEP, 2014c]

Figure 4. Projected annual savings from the top six product categories in 2013



Country-by-country analyses leading political commitment

UNEP and its partners have developed country-by-country savings estimates showing energy, environmental, and financial benefits, which are achievable with a transition to energy efficient products. First came the country lighting assessments (CLAs), which are now available for 150 countries for on-grid lighting products. The country assessments provided the first arguments in discussion with government decisions makers and stakeholder on benefits of transition their market to energy efficient lighting.

According to the analysis, a transition to efficient lighting in all end-use sectors in on-grid lighting (residential, commercial and industrial sectors, for indoor and outdoor applications) would save over $120 billion annually in avoided electricity bills through a reduction of 1044 TWh of electricity. The magnitude of these global energy savings represents approximately 37% of electricity use annually for lighting globally and approximately 350 GW in avoided electricity-generating capacity. This electrical capacity would be enough to electrify approximately one billion households. [UNEP, 2014a]

Further, UNEP will develop similar country assessments for next four high-impact products (room air conditioners, residential refrigerators, electric motors and distribution transformers).

These assessments have already been completed for Latin America and the Caribbean and the Southern Africa, where the partnership has already begun engaging with decision makers, regional bodies, and utilities. These activities are described in more detail below:

Latin America and the Caribbean

In collaboration with CLASP, UNEP developed country assessments on the thirty-three Latin America and Caribbean countries for three cooling products: refrigerators, air conditioners, and fans. The results of the study showed a very sharp increase in the stock of the three products by 2030, including an increase of over 120% for refrigerators in Paraguay, over 400% for air conditioners in Panama and nearly 70% for fans in Belize.

As impressive as the growth of products is, the saving potential of a transformed market are even more inspiring. If all countries in the region were to implement policies by the year 2020, the analysis shows that over 140 terrawatt hours could be saved annual, equal to about 11 percent of the region's current electricity consumption. Further, these savings would result in a reduction of 20 billion US$ due to reduced electricity bills and also reduce greenhouse gas emissions by 44 million tonnes, equivalent to taking 24 million cars off the road. [UNEP, 2014b]

Southern Africa

In preparation for a Southern African Power Pool (SAPP) and UNEP hosted workshop on the *Regional Roadmap for Leapfrogging to Efficient Lighting, Appliances, and Equipment in Southern Africa,* UNEP and CLASP developed country assessments for the SAPP member countries on three high-impact products for the region (refrigerators, air conditioners, and distribution transformers). According to the analysis, a transformation to high-efficiency products would each year save the region more than 22 TWh or 5% of future electricity use, which would allow for grid connection to an additional ten million households and also save consumers nearly two billion US$ on electricity bills. Further, the environmental impacts are profound with emission reduction potential of over 10 million tonnes of CO_2 per annum, which is equivalent to taking over 5 million cars off the road. [UNEP, 2015]

By preparing the country sheets, it provided an opportunity to discuss and agree on an action plan for utilities, government officials, and private sector companies on the large potential savings that are possible. At the workshop, the official communiqué included the following achievements, amongst others:

- Advanced lighting solutions, efficient appliances and modern equipment are fundamental to decouple economic growth from an ever-increasing energy demand.

- There was agreement among the participants with a movement towards regional harmonized standards, which offers an effective way to achieve high product compliance, reduce costs to set-up monitoring, verification and enforcement mechanisms, and limit the cost of efficient products by fostering regional trade.

- Workshop participants suggested to prioritize lighting, refrigerators, air conditioners, water heaters and distribution transformers as high-impact opportunities offering the most cost-effective and fastest way to save energy in the region.

Case study: regional approach to energy efficient lighting in West Africa

West Africa offers an excellent example of a regional approach to advance energy efficiency. In collaboration with the Economic Community of West African States (ECOWAS) Centre for Renewable Energy and Energy Efficiency (ECREEE), government representatives were able to establish a regionally coordinated framework to transition to energy efficient on- and off-grid lighting in April 2014. The regional strategy establishes:

- Common minimum energy performance standards for on- and off-grid lighting. The standards will enable the phase-out of inefficient lighting between 2016 and 2020.
- Implementation of common market surveillance systems, with two regional accredited laboratories to improve product quality in the marketplace;
- Harmonized mandatory labeling and certification scheme for both on- and off-grid efficient lighting and preferential tariff and fiscal structure for efficient lighting products;
- Establishment of an ECOWAS directive on the collection, treatment and recycling of electric waste, with a specific focus on lighting products.

By taking a regionally harmonized approach, the countries will benefit from the high efficient products being able to flow between countries and also reduce the likelihood of non-compliant goods flowing through the porous borders. Further, cost of implementation will be reduced due to synergies in implementing common testing laboratories and recycling systems.

Through implementing the strategy for on- and off-grid lighting, UNEP projects that ECOWAS will avoid 12.3 Mt of CO_2 emissions, save 3.9 billion litres of kerosene and save 2.4 TWh of electricity consumption, equivalent to 4 billion US$ annually.

Conclusions

Advancing energy efficiency of lighting, appliances, and equipment, provides a large opportunity to contribute to keeping climate change at a two-degree warming scenario. Not only does energy efficiency provide large environmental benefits, it is also extremely cost effective, providing increased expandable income for end-users. Developing and emerging countries are uniquely positioned today to leapfrog over lower-efficiency products to advanced products that provide energy, financial, and environmental benefits.

To achieve the market transformation, five key recommendations are provided:

- Action is needed today in order to avoid further lock-in of inefficient products. If policies are implemented at a slower rate, it will cost developing countries greatly as the purchase of lighting products and appliances such as refrigerators is expected to grow immensely in the coming years. Under the SE4ALL initiative, UNEP and its partners stand ready to support countries in capitalizing on the benefits of a market transformation to energy efficient lighting, appliances, and equipment.
- Country assessments showing the potential savings, including energy, financial, and environmental benefits, provide the first step in gaining political commitment from government and private sector decision-makers. The approach has assisted in the gaining of sixty-six country partners to commit to transforming their markets to energy efficient products.
- The inclusive approach of the Efficient Appliances and Equipment Global Partnership Programme provides diverse competencies, yet the partners are strategically chosen for their commitment to advancing energy efficiency. The partnership also shows the potential to work with private sector manufacturers to advance regulation, strategies, and projects to accelerate the market transformation of energy-efficient products. The partnership also provides effective collaboration between international organizations, with each contributing its strengths,

whether it is on gaining global political commitment, in-country implementation, or the development of financial mechanisms.

- The integrated policy approach is a holistic one that has been successful throughout OECD countries and now should be expanded to a greater number of countries outside the OECD. The experience of developing countries that have utilized the integrated policy approach for lighting under the en.lighten initiative shows that large financial, energy and environmental benefits are available. With the support of policy guidance from the en.lighten initiative, the approach also has proven flexible for countries to adapt to their national circumstances and also to adopt across a wide range of products, including lighting, appliances, and equipment.
- Regional approaches and harmonization can greatly aid in the successful development and implementation of policies and standards. As lighting products, appliances, and equipment are traded across borders, regional collaboration can reduce the duplication of standards, which will assist in the understanding of both consumers and industries; reduce cost of implementation for producers and distributers; and reduce non-tariff trade barriers.

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Harnessing appliance energy efficiency in South Africa: Policy gaps and recommendations to address actor-specific barriers

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Abstract

The residential sector is the second largest consumer of electricity in South Africa. Peak loads that often exceed supply and related power blackouts are persistent concerns. Electricity tariffs for residential consumers tripled over the period 2008-2012 and will increase by a minimum of 12% per annum up until 2017. In contrast, scenario calculations show that significant amounts of energy could be saved with the most efficient appliances. In combination with ambitious sustainability targets, strong arguments exist for the broad usage of efficient appliances and the implementation of adequate policies. As every country, South Africa has implementation barriers, which need to be tackled by specific policies and measures to adjust market-inherent incentives. Thereby, single policies have to be combined to create an appropriate policy package addressing demand and supply side.

The South African government began establishing policies for energy efficiency in 2005. Since then, the country has already developed a considerable energy policy framework, including a mandatory Standards and Labelling Programme for residential appliances which will come into effect in 2015. However, compared to other countries, South Africa's overall policy package for energy efficiency is still less comprehensive. This paper will analyse the current situation in South Africa and compare it with the recommended appliance-specific policy package developed by bigEE.net [1]. Policy gaps will be assessed and actor-specific barriers described. As a result, strategies will be identified to advice national policy makers how to increase energy efficiency with innovative new policies and with the further development of existing policies.

Introduction

Energy Background

Due to the fact that coal is widely and cheaply available in South Africa, the country was able to generate electricity at very low prices. Electricity costs for consumers were traditionally very low and electricity tariffs in South Africa were amongst the lowest in the world in 1995 [2]. Between 1960 and 1990, the government built large, coal fired electricity plants with a nominal generation capacity of 35 GW. When the new democratically elected government came into power in 1994 the country had excess supply and was able to undertake a massive electrification programme. Access to electricity meant that more households were now in a position to use electrical appliances, which resulted in a boom for the overall market of these products.

With a share of 17.2%, the residential sector is the second largest consumer of electricity in South Africa. However, in recent years the country had to deal with several bottlenecks in the supply of electricity due to rising overall energy demand. The South African government was forced to increase energy production and to balance energy demand at the same time to stabilise the power grid. Nevertheless, occurring peak loads with a magnitude that often exceed available generation capacities and related power blackouts remain persistent concerns. To fund two new coal-fired power stations (9.6 GW), which are over-budget and five years behind schedule, electricity tariffs tripled over the period 2008-2012 and will increase by at least 12% per annum until 2017. In 2015, a residential customer in South Africa has to pay about 10 Eurocent per kilowatt-hour [2].

For that reason, first regulations for the diversification of the energy market and the integration of renewable energies were developed in the last 10-15 years. The South African government has defined the aim to make the energy market more sustainable in the future – to guarantee energy security and emission reductions – and to focus also more on renewable energies and energy efficiency. However, to cover the high demand, South Africa still increases the use of national coal reserves and with about 85% of the country's electricity generation, coal nevertheless dominates the energy market. This trend is also closely related to the energy-intensive economic sectors in South Africa, such as mining and metal refining industries. Another characteristic of the energy market is the monopolistic structure of the energy utilities. The state-owned utility Eskom supplies up to 95% of the South African energy market with electricity, whereas the liberalisation of the electricity market has just begun [3].

South Africa in the face of Energy Efficiency

The omnipresent shortage of supply, the energy intensive industry, the overstrained coal fired power generation, ambitious national climate goals and especially the resulting surge of electricity prices pushed the energy topic on the political agenda in South Africa. As consequence, energy efficiency has been identified as one of the essential measures to overcome this situation. In this context, the South African government adopted the "National Energy Efficiency Strategy" (NEES) in 2005 and the "Electricity Regulation Act" in 2008 to promote energy efficiency and to minimize energy consumption. Among other aspects, the NEES defined a national voluntary target for energy efficiency improvement of 12% by 2015 compared to a 2000 baseline. Furthermore, sector-specific targets were set e.g. for industry, the residential sector and transport [3]. Since then, South Africa has already developed a considerable energy policy framework, including a forthcoming mandatory Standards and Labelling Programme for 12 appliance groups.

Despite these efforts, compared to other countries, South Africa just begun to focus on energy efficiency and thus the overall policy package has several shortcomings and is still less comprehensive. However, to initiate and foster market transformation towards energy-efficiency it is highly advisable for policymakers to overcome country-specific market barriers and to take necessary measures. In order to tackle each of these obstacles as well as to adjust market-inherent incentives, specific policies and measures are required. To address the demand and supply side actors at the same time, individual policies have to be thoughtfully combined in order to create an appropriate and powerful policy package.

This becomes even more relevant for the appliances sector, as results from scenario calculations carried out by bigEE.net show that significant amounts of energy could be saved with the most efficient appliances available today [4]. These savings are usually very cost-effective. Therefore and in combination with ambitious sustainability targets, strong arguments exist for the broad usage of efficient appliances and the implementation of adequate product-specific policies. The next chapters will further elaborate these topics and focus on refrigerators and freezers.

Energy efficiency potentials for appliances in South Africa

Current situation

As recently as the late 1980s the electrification rate for residential households was low in South Africa, whereby almost all white households had electricity and non-white households did not. An electrification programme was successfully implemented in the early 1990s, which expanded the market for electrical appliances considerably. Nevertheless, the country's persisting and significant income inequality means that the middle to lower end of the market chooses appliances almost exclusively based on price and brand. These appliances typically have less functionality and are often higher consumers of electricity. Conversely, upper income households choose their appliances based on functionality, design, brand, guarantees and after sales service, aesthetics and to a lesser extent and only more recently on their energy consumption. Consequently, South Africa has developed a pronounced two-tier consumer base, with each group supporting different brands, models and efficiency levels [2]. Exemplarily, this paper analyses the energy efficiency potentials for refrigeration appliances as case study.

Case study: Saving potential for refrigeration appliances

As cold appliances have a very high household penetration rate (> 80%), operate 24/7 and have also a technical product lifespan of more than 10 years, a reduction of the unit energy consumption (UEC) of appliances will result immediately in relevant energy and cost savings for the country and the consumers. This paper focuses on the two most popular product sub-categories of the refrigeration market in South Africa: Fridge/Freezers and Freezers.

Fridge/Freezers

Approximately 7.4 million Fridge/freezers were in use in South Africa in the chosen reference year 2010 (starting year of the scenario analysis). The average annual consumption of each of these Fridge/freezers amounted to about 472 kWh. In total, this caused an annual electricity consumption of 3.5 TWh (see Figure 1). The calculations of the Efficiency scenario (B) are based on the assumption that every time a new Fridge/freezer is bought, the most efficient "Best Available Technology" (BAT) model is chosen and that the improvements of the most efficient models over the years are taken into account. For comparison, the baseline or "Business As Usual" (BAU) scenario (A) assumes a development without further ambitious energy efficiency policies and therefore a continuation of current tendencies regarding size, use and efficiency of appliances sold on the market.

By this means, in the Efficiency scenario (B), an absolute decoupling of the annual energy consumption and the increasing stock of Fridge/freezers can be achieved. While the stock is expected to grow by 55 % between 2010 and 2020, in the efficiency scenario the energy consumption can be reduced by 21 %. Although the stock is expected to grow by another 41 % until 2030, in the efficiency scenario the energy consumption would further decrease by 20 % (see figure 1). Thereby, higher living standards (e.g. increasing appliance ownership rates and household numbers) have been anticipated. In contrast, in the baseline scenario with only moderate assumed efficiency gains the energy consumption would increase by 17 % until 2020 and by 7 % between 2020 and 2030 [2].

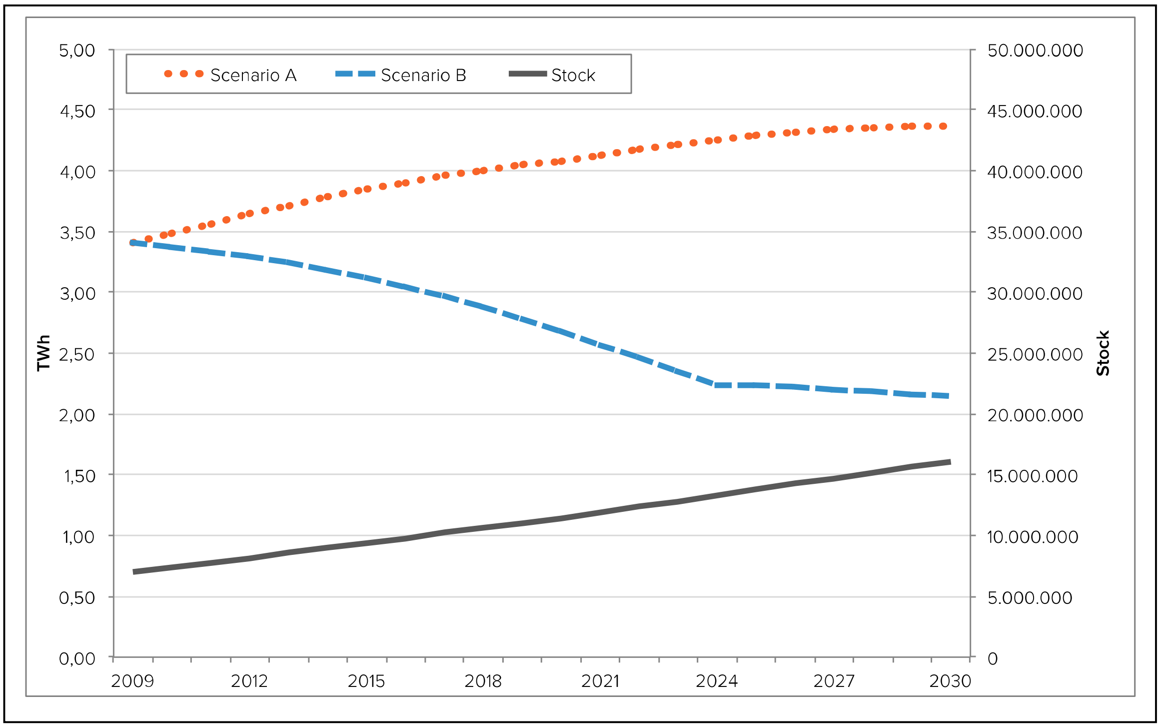

Figure 1: Total electricity consumption and stock of Fridge/freezers in South Africa

Source: [2] Note: Baseline Scenario (A) vs. Efficiency Scenario (B)

Freezers

In respect of freezers, about 3.5 million appliances were in use in South Africa in 2010. With an average annual unit consumption of 473 kWh the total annual electricity consumption amounted to 1.6 TWh. Based on the performed model calculations, efficiency improvements can also be achieved for this product group, especially if old inefficient models are replaced by modern efficient ones.

In contrast to the fridge/freezers, the freezer market in South Africa was almost exclusively supplied by local manufacturers until 2010. These low-cost local freezer products were mainly built for the South African market and were characterized by poor energy efficiency ratings compared to international standards. In recent years local manufacturers have upgraded their product lines to improve the efficiency and at the same time international companies have increased their market share [2]. The calculations of the Efficiency scenario (B) are also based on the assumption that every time a new freezer is bought, the most efficient “Best Available Technology” (BAT) model is chosen and that the improvements of the most efficient models over the years are taken into account. As for fridge/freezers, also the baseline (BAU) scenario (A) for freezers assumes a development without further ambitious energy efficiency policies and therefore a continuation of current tendencies regarding size, use and efficiency of products sold on the market.

By this means, in the Efficiency scenario (B), an absolute decoupling of the annual energy consumption and the increasing stock of freezers can be achieved until 2030. While the stock is expected to grow by 55 % between 2010 and 2020, in the efficiency scenario the rise of the energy consumption can be mitigated to 11 %. Although the stock is expected to grow by another 44 % until 2030, in the efficiency scenario the energy consumption would even decrease by 19 % (see Figure 2). Thereby, higher living standards, represented by increasing appliance ownership rates and household numbers, have been anticipated. In contrast, in the baseline scenario (A) with moderate efficiency gains the energy consumption would increase by 26 % until 2020.

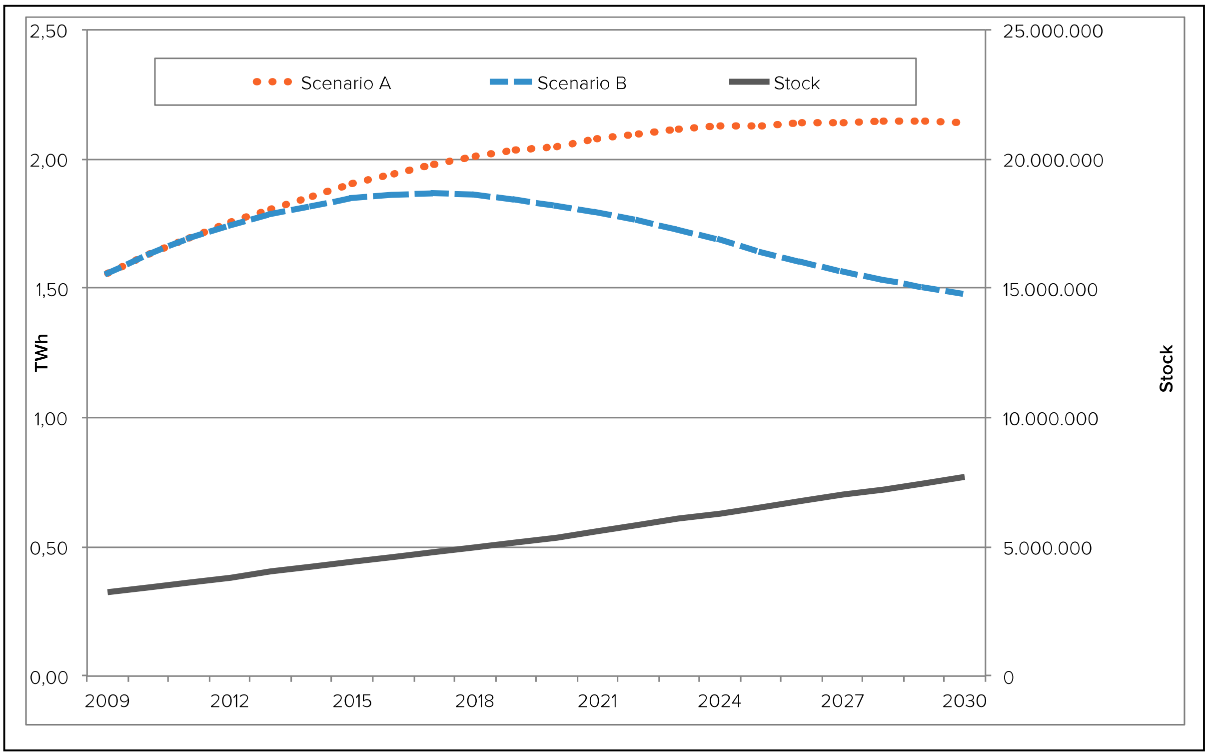

Figure 2: Total electricity consumption and stock of Freezers in South Africa

Source: bigEE.net [2] Note: Baseline Scenario (A) vs. Efficiency Scenario (B)

The above-presented results from bigEE.net scenario calculations for Fridge/freezers and Freezers show that significant amounts of energy could be saved with the most efficient appliances. These savings are usually also very cost-effective for the country and the consumers. Therefore and in combination with ambitious sustainability targets, strong arguments exist for the broad usage of efficient appliances and the implementation of adequate policies to support a much faster diffusion of the most innovative technologies.

Barriers in the appliance sector

The previous section and the example of refrigeration appliances have shown that enormous saving potentials can be realised by improving the energy efficiency of appliances. Most of the available improvement options are also cost-effective from a life-cycle perspective if they are realised during the purchase of new products or as integral part of normal reinvestment cycles. Nevertheless, many studies have also illustrated that these energy savings are often not realised by market forces alone, due to a variety of barriers and market failures [1]. By knowing the country specific barriers and possible incentives, the policy package can be adapted to guarantee desired results and achieve the greatest possible energy savings. Some of the main barriers for further energy efficiency gains in South Africa are listed below. The barriers are ranked from the most critical to the less critical.

Electricity prices

Almost all residential appliances in South Africa are electrical. As historically there was a low unit price of electricity, many customers got used to cheap energy as a minor input cost factor and are therefore not motivated to reduce energy consumption. This is a strong barrier because interventions cannot be justified in case of lengthy payback periods [5]. However, in 2009 the South African government started increasing the electricity tariffs to reflect their true costs with the Multi Year Price Determination (MYPD). The costs increased by 31.3 % in 2009/10, 24.8 % in 2010/11, 25.8 % in 2011/12 and by 16 % in 2012/13 [3], reaching about 10 Eurocent per kilowatt-hour for consumers in 2015.

Institutional barriers

In the public sector, the lack of co-ordination mechanisms is a problem in many countries. As long as there is a lack of resources and capacities in the public sector, policies will not be as effective as possible. Some measures in South Africa have also performed poorly because key positions are poorly staffed, under resourced and not adequately skilled. Furthermore, policies should be mandatory because as long as programmes remain voluntary, several actors will take little notice of them.

Institutional barriers can also exist within the application of policies. E.g. companies often do not have a dedicated department responsible for energy efficiency improvements and the management of energy consumption [6]. Furthermore, according to the Department of Minerals and Energy (2004) “there is a frequently encountered misconception […] that energy efficiency will disrupt production processes and that changes should not be made unless absolutely necessary. There is a fear of interrupting running processes as long as they work” [3].

Lack of financial incentives

Capital constrains and risk aversion of investors can inhibit uptake of energy efficiency measures. On the demand side of energy efficiency markets, these barriers relate to the required upfront investment and the relatively lengthy payback periods, combined with uncertainties about the future. For suppliers there is a risk of new energy-efficient solutions not meeting with sufficient demand [1].

Lack of awareness and information

Consumers are often unaware that energy efficiency potentials exist. Most people and companies in South Africa are simply not yet aware of the energy saving options and even if they know about, they are usually not sufficiently informed about the real costs and benefits [1]. There is also an uncertainty that the energy savings may not be actually realised. Even obvious “low hanging fruits”, which could be implemented with little investment and technical effort, are therefore often not realised. Besides the misjudgement of the financial efforts, the knowledge of consumption data is often only rudimentary. This prevents the identification of saving potentials and the success verification of energy efficiency investments [3].

Low priority

South Africa as an emerging country has to struggle with different national challenges, like ensuring the quality of life and education. Consequently, energy efficiency has not had the highest priority in the country. Business-as-usual practices remain where energy efficiency has a low priority [6].

Investor-user barrier

So-called split incentives occur when the investor bearing the costs of an energy efficiency improvement is not the one directly benefitting from it. This remains a key barrier in the residential, commercial and public building sectors. For the former the tenant is often unwilling to make a capital investment in a rented property even if the returns are positive as it is seen to be enriching the landlord. Conversely the landlord will not upgrade equipment as no direct financial benefit accrues. This barrier is not unique to South Africa. However, the problem is even more acute e.g. in the South African public sector as the structural arrangements are such that all buildings are owned and controlled by a specific department, for example the Department of Public Works (DPW) for the national Government. Ministries occupying these buildings are generally not charged for energy usage and thus have no interest or incentive to use them efficiently.

The recommended policy package approach

To move the South African market towards the best available technologies, policy makers have to pay attention to the specific barriers for the different market actors. Several policy instruments need to interact and reinforce each other in a comprehensive policy package. As pro-active countries have demonstrated (see bigee.net), a comprehensive and coherent policy package for energy efficiency will usually provide a sound balance between clear ambitious mandatory measures, incentives, information as well as capacity building. It also needs a well functioning governance framework to enable an effective implementation of these policies. Figure 3 illustrates an “ideal” policy package for appliances, which consists of the governance framework and specific instruments. The governance framework includes the categories “targets and planning”, “infrastructure and funding” and “eliminating distortions”. Furthermore different sub-categories of these three categories are shown. These sub-categories are possible instruments to increase energy efficiency in appliances. Furthermore there are specific policies and measures, which are illustrated in the lower part of the figure. These are “regulation”, “transparency and information”, “incentives and financing”, “capacity building and networking” as well as “RD&D and BAT promotion”. Some of the sub-categories (e.g. MEPS as a sub-category of regulation) are explained in the next section.

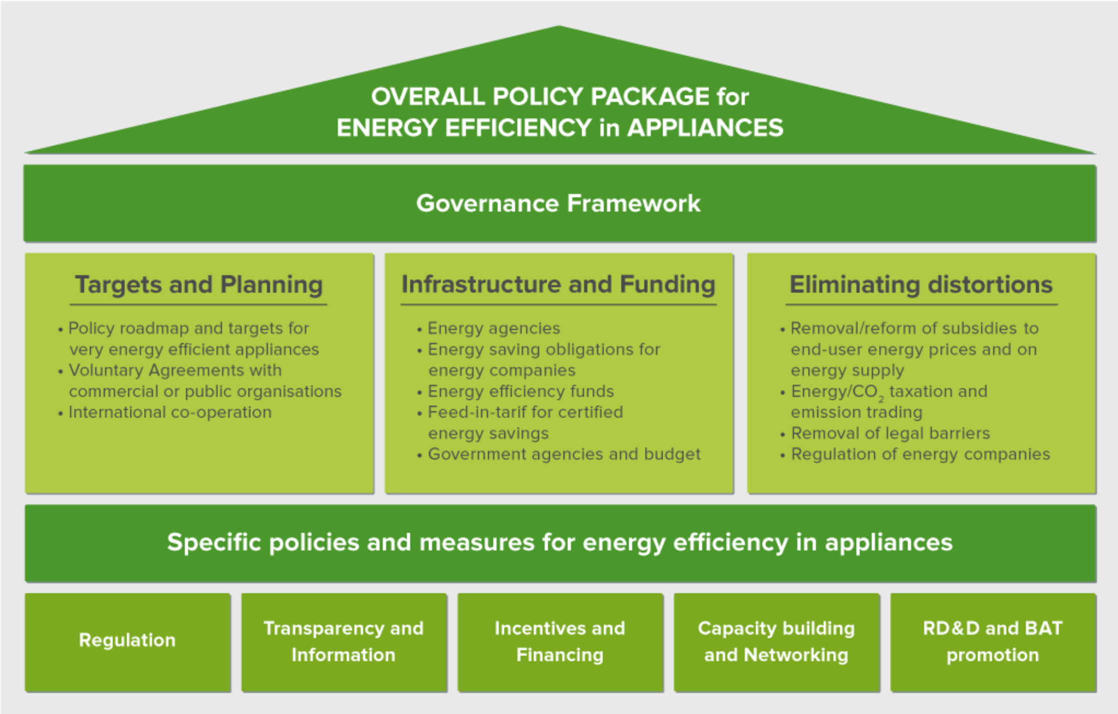

Figure 3: The recommended policy package

Source: [1]

Legal provisions on minimum energy performance standards (MEPS) reduce search and transaction costs and help to reduce the investor-user dilemma. They are a cost-effective way to eliminate the segment of the worst energy-performing products from the market. However, they do not harness additional savings potentials due the most energy-efficient products in such cases. Therefore minimum standards are often combined with labelling and rebate schemes. This gives additional incentives for investments beyond the level required by the MEPS. Financial or other incentives can give the decisive impulse that makes people opt for the more energy-efficient investments. In addition, financing instruments such as soft loans are often needed to overcome potential incremental costs for BAT products and to enable investors to make more sustainable upfront investments.

To intensify effects towards energy efficiency, information programmes, training of sales staff and manufacturers, and especially green (public) procurement programmes can also influence positively the market to promote energy efficient appliances. With procurement programmes but also with bulk purchasing projects and competitions it is even possible to go beyond the BAT and to support a market development towards the most innovative technologies with very high energy-efficiency levels.

The next chapter will present the existing instruments of the current country-specific policy package in South Africa with a focus on Standards & Labelling and Financial Incentives, as well as selected complementary instruments also illustrated in Figure 3 under “Specific policies and measures for energy efficiency in appliances”. Furthermore a gap analysis will be included to highlight the missing policy package components and to demonstrate also opportunities for national policy making.

The appliances-related policy package in South Africa – Gap analysis

The opportunity for energy efficiency in the appliance sector was recognised by the South African government as far back as the mid-1990s. However, electricity tariffs in the country were amongst the lowest in the world at that time, resulting in little incentives to act. Thus, although the South African Energy White Paper identified specific programmes and measures already in 1998, it was the introduction of the National Energy Efficiency Strategy (NEES) in 2005 that marked the actual beginning of dedicated policy formation, when the security of power supply deteriorated and energy prices began to rise [7]. Thus, an earlier implementation of adequate policies could have mitigated or even avoided large-scale power failures, which affected the economy negatively [8]. Furthermore voluntary policy targets do not express a strong political commitment to energy efficiency and some key measures are still waiting to be implemented.

To enable further progress, the government commissioned the South African National Energy Development Institute (SANEDI) as the national energy agency and gave the national utility Eskom the responsibility for financing energy efficiency measures under a Demand-Side-Management (DSM) programme.

Standards and Labelling

In 2005/06, the government of South Africa introduced a voluntary label for refrigerators, which was the intended precursor to a mandatory standards and labelling programme. It was decided to adopt the EU energy label format and a label was designed for the South African market. The voluntary programme had very limited impact. In 2008, the South African Bureau of Standards (SABS) formed therefore a working group to develop a new South African National Standard (SANS 941), which identifies energy efficiency requirements, energy efficiency labelling, measurement methods and the maximum allowable standby power for a set of appliances as basis for introducing a mandatory regulation.

However, due to barriers such as lack of funding and a low priority assigned to this initiative, it took a long period between the planning of the performance standards and the actual implementation. Finally, the South African Minister of Trade and Industry published mandatory performance standards in the 'Compulsory Specification for Energy Efficiency and Labelling of Electrical and Electronic Apparatus' [9] on 28 November 2014, coming into force as of 2015. The first set of appliances selected for the programme includes refrigerators, washing machines, dryers, dishwashers, electric water heaters, ovens, A/C and heat pumps.

To illustrate the effects of the delayed policy process, again the example of refrigerating appliances is presented as case study.

S&L case study: Refrigeration appliances

The South African S&L programme sets the MEPS implementation date for refrigerators and freezers on 28 August 2015, with label class B as the highest to remain on the market for refrigerators and C for freezers [9]. In order to analyse the potential impact of the new S&L programme, it is essential to evaluate the preceding market baseline. It must be assessed whether and when a potential improvement in energy performance has already resulted or will result from the new regulation. For this purpose 2010 is used as the baseline year and 2014 for comparison (as preceding year before MEPS come into effect).

Regarding the general distribution of the stated energy rating, it was found for the covered product energy classes that the concentration of models were at A and better or D and worse, with few models being found in the classes B and C [2]. This may be explained by the characteristic two-tier consumer base, whereby imported models account typically for the A and better energy classes and locally manufactured low-cost models (which were only sold in SA) for the other end of the energy efficiency scale.

The long absence of mandatory performance standards and little interest from consumers meant that no energy performance improvements were made especially to the poorly performing local models. However, it must be noted that the 2010 numbers of models and the energy class levels were provided by the six major manufacturers with no additional research. For 2014, energy classes of appliances are based on manufacturer responses and information available on product websites. As each manufacturer may have also interpreted the request for data differently, it is assumed to be a representative but not a full list of models available per manufacturer in the reference years. For example, ranges which were coming to an end or which had been discontinued may have been excluded even though they were still widely available. Due to the lack of mandatory information requirements in SA, the provided data also cannot be officially verified by other sources. Nevertheless, although not a complete list, it is believed to cover reliably the majority of the market in South Africa.

The market distributions of the available models per energy rating for the 2010 baseline year and for 2014 are displayed in the following figures 4 and 5.

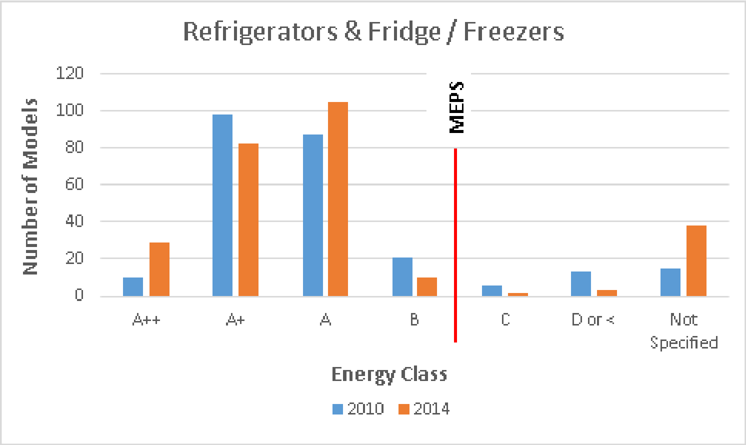

Figure 4: Comparison of 2010 and 2014 stated energy rating of Fridge/freezer models

Source: [2]

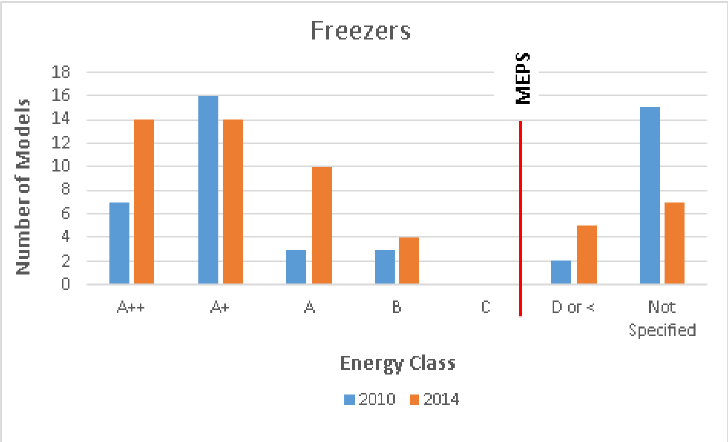

Figure 5: Comparison of 2010 and 2014 stated energy rating of Freezer models.

Source: [2]

The surveyed manufacturers have furthermore indicated that for the appliances that are to be included in the S&L programme their product ranges meet the MEPS and that they would like to see the programme to come into effect as soon as possible. Until 2015, it was with the retailers where the uncertainty mainly persisted, as the delayed implementation of the mandatory S&L programme meant that stores remained unclear on the required information to be provided with the products. This resulted in a situation where it was left up to the individual store manager, who may not be familiar with the programme, to decide as to whether appliances labels are displayed and how to best deal with appliances where the energy efficiency rating was not supplied by the manufacturer. Up to 2015, the consequence is that in the stores some appliances have labels, others do not and actually used labels are still not standardised (as they are commonly the different label versions from the originating countries of the appliances).

A comparison of the 2010 and 2014 energy class distributions shows that:

- In 2014 the majority of the models meets the MEPS, few do not and a certain number includes 'unspecified products', whereas in 2010 there were less qualifying models. In both cases the number of non-qualifying models makes up only a small percentage of the total number of models available, but what can be inferred is that the manufacturers have already started the phasing-out of models, which do not meet the 2015 MEPS.

- Conversely, the number of available efficient and very efficient models increased also significantly from 2010 to 2014.

- The high number of 'unspecified' models in 2010 for the freezer category was primarily made up of locally manufactured models, which had never been tested according to international standards as there was no requirement to do so and no accredited testing laboratory existed. Manufacturers accepted that these low-cost units would fare poorly (energy class E or less). Thus, setting the MEPS for freezers at energy class C, and not B, can be also interpreted as concession to support the local manufacturing industry, based on the 2010 product lines.

- Nevertheless, the figures show a distinct decrease in the number of unspecified freezer models from 2010 to 2014 as well as increases in the A and B energy classes. This suggests that local models have also been improved in the meantime to meet the MEPS. Interestingly, with no more available models found actually in the C category, a 2015 MEPS level of B for freezers would have been obviously also possible for local manufacturers**.**

- Finally, it is not exactly known to what extent the currently remaining unspecified models are poor performing models or whether these models have just not been labelled as there is no requirement to do so. In all likelihood it is a combination of the two reasons.

The overall numbers of available refrigerating appliances found on the South African market for 2010 and 2014 are very similar. Since the model numbers originate from the same market-leading manufacturers, similar brands are represented and thus the resulting market overviews can be considered as normalized and sound data sets. As noted above, the changes in the efficiency range of the models between 2010 and 2014 may be most likely attributed to model ranges that have been upgraded and shifted in direction of higher efficiency classes. E.g. where a manufacturer may have had more A+ models in 2010, the current stock representation may have shifted in that there are currently fewer A+ models but more A++. Although the delay of the S&L programme has also resulted in a persisting market share of appliances whose energy rating is still unknown or unspecified, it can be concluded that the market average efficiency has already improved significantly within the analysed time period.

Consequently, no substantial further energy savings from residential cold appliances can be expected anymore when the S&L programme comes finally into effect, as the 2015 MEPS level is already mostly obsolete due to the observed development of the average market weighted unit energy consumption and the related efficiency class distribution.

Financing programmes and financial incentives

Under its umbrella programme "Energy Efficiency and Demand-Side Management" (EEDSM), the South African utility company Eskom offered financing support and is able to recover related expenses through the tariff revenues it generates. Sub-programmes (see figure 6) are e.g. contracting programmes, residential mass rollout projects and standard offer models. E.g. small projects under 250 kW are supported with the standard product programme. It provides pre-approved rebates for technologies like efficient lighting, shower heads, air conditioners, heat pumps etc. The payment is between R0.5 and R1.0 per kWh and based on the product installed as well as on a standard value per item.

Another programme under the EEDSM scheme is a solar water heater (SWH) rebate programme to install one million SWH, as the current broad provision of electric domestic hot water consumes as much as 40% of the average energy use in a middle-income home in South Africa [10]. This means that the right products were targeted. Other measures are the Residential Mass Rollout (RMR) and the Compact-Fluorescent Lamp (CFL) programme. For the latter, Eskom bulk-purchased and distributed CFLs for free to households between 2004 and 2012. During that period, 54 million lamps were replaced resulting in 2,173 MW demand savings. Larger energy savings from 50 kW to 5 MW were also incentivized through the "Standard Offer Programme (SOP) launched in 2010. Eskom approved projects receive around 0.55 South African Cent per kWh over a three-year period. Technologies, which qualified for SOP funding, include lighting and hot water systems. Since savings must be achieved within a defined period of the day (between 06:00 am and 10:00 pm), the programme has aimed at reducing peak demand in particular [11] [7]. According to [12], the SOP overall energy savings amounted to 209 GWh between 2010 and 2012.

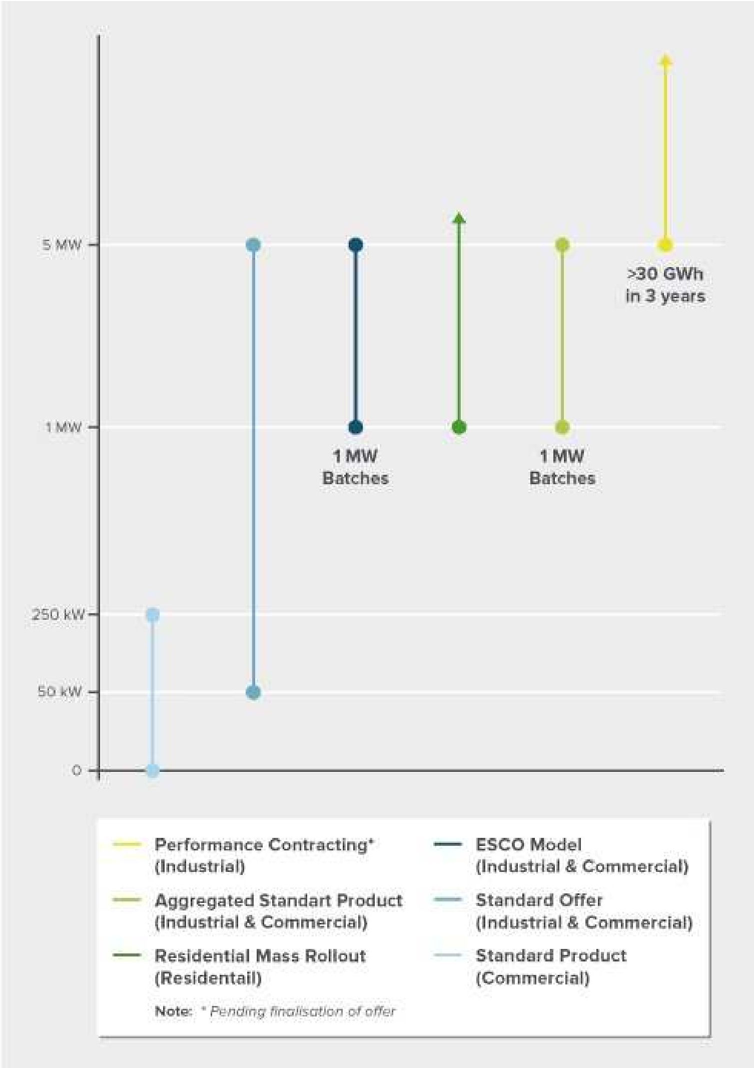

Figure 6: Eskom Funding Models

Source: [15]

In the context of energy efficiency financing, it is important to notice again that the state-owned utility Eskom generates almost all of South Africa's electricity. The resulting conflict of interest between DSM and revenue generation within Eskom has been a big barrier. For example, there was a greater support for load shifting rather than overall load reduction. Finally, besides other general funding problems, this was one reason why Eskom abandoned the EEDSM in October 2013. Another problem of the programme was also a general lack of process transparency. Criteria for financing support in South Africa have been largely non-transparent, which has "led to substantial delays and costs to the project developers, and often erected a major disincentive [13]".

An indirect successor of the DSM programme is the 12L initiative. This programme provides incentives for businesses that can show measureable energy savings. A tax deduction, claimable until 2020, is valid for all energy forms (not only electricity) and energy efficiency projects that reduce energy use. However the effective rebate is just R 0.126 (less than 0.01 EUR) per kWh [16] making it financially unattractive for many companies. Additionally, the related measurement and verification (M&V) requirements are also onerous making them time consuming and expensive.

Complementary policies: information campaigns and public procurement

Positive examples for additional measures are the energy efficiency information campaigns in South Africa. One of Eskom's core awareness raising measures is the "49M Initiative" (referring to the country's 49 million inhabitants) launched in 2011. The aim of the campaign is to inform people about energy efficiency, to change their consumption habits and to, eventually, realise energy savings. Between March and December 2011, the 49M Initiative reached more than 500,000 people directly and several millions through radio commercials and newspaper articles [14]. A second and more direct campaign is Eskom's Power Alert initiative, which uses television adverts during peak periods that show the current status of the power grid and requests households to switch off non-essential appliances when the grid is overloaded or unstable. However, as with the EEDSM programme, Eskom's complementary energy efficiency campaigns have been reduced recently due to financial constraints of the company.

Another relevant opportunity for policy making in the context of supportive measures would be to address the missing implementation of energy efficiency programmes in the public sector of South Africa. Although there are already plans to introduce e.g. public procurement programmes, no actual measure has been developed to date. Again, delays are partly the result of a lack of skills and resources for policy implementation. Introducing energy efficiency programmes in public buildings has already proven to be difficult due to many bureaucratic and procedural obstacles. There appears also to be limited political will in certain areas and consequently, e.g. after multiple years of not spending its allocated budget, the National Treasury withdrew the reserved funding from the Department of Public Works.

Conclusions

Overall, the South African energy efficiency policy and the related market for energy efficiency technologies are on the rise. The adoption of the national energy efficiency strategy and the associated introduction of efficiency targets as well as several financial support programmes established a first foundation for an energy efficiency policy framework. The shortage of electricity and the rising energy price until at least 2018 should already provide strong incentives for policy makers and other stakeholders to implement a more comprehensive overall policy package and to further increase energy efficiency with additional measures. Investors also begin to understand that energy consumption is a highly relevant cost factor that should be minimized, also to strengthen the international competitiveness.

However, the performed gap analysis demonstrated that due to missing, ineffective or already abandoned policies and measures, South Africa is still at the beginning of a more comprehensive energy efficiency strategy and much remains to be done to ensure a fast and successful transition of the energy market.

- The Eskom EEDSM can be considered as very successful programme, yielding about 3,500 MW of demand savings. However, as it was still not comprehensive enough (e.g. to directly support the S&L programme for appliances), it is also an example for the lack of coordination between government institutions.

- Despite the enormous saving potentials, the successful EEDSM programme has been suspended since 2013 and to date no direct and adequate successor has been announced to replace or even to extend it. The country is rightly focusing on energy security, but if energy efficiency as elementary aspect is neglected all the gains made since 2007 will be marginalised, which would make it even much harder to achieve the national development targets.

- Other programmes are postponed or less ambitious than required. E.g., although the delay in implementing the S&L for appliances may have supported old products of the local manufacturing industry for a very limited period, it was regarding the lost local innovation potential and the cost disadvantages for all the other national stakeholders a definite drawback. Any further improvement in the average appliance efficiency classes would have directly translated into savings for the society and consumers, which have now been lost and related GHG emissions have been also locked-in for years. Additionally, at least some of the S&L requirements are already out-dated and not ambitious enough to realise the significant energy and cost saving potential and to transform the market.

- Another example is the planned carbon tax in SA. The original Carbon Tax Policy Paper issued by the National Treasury announced 2015 as the starting year for the taxation scheme [17]. However, in two successive national budgets the start date has been postponed. Due to a very strong general opposition to the carbon tax from different interest groups, there is a reasonable chance that this programme (which could provide major incentives to act) may be finally abandoned.

To address the identified policy gaps, a selection of policy recommendations is given below.

Policy recommendations

Political commitment to Energy Efficiency and the Policy Package approach

- Strengthen in general the good governance framework in the public sector
- Address doubts regarding possible positive economic effects of energy efficiency and the related lack of implementation motivation and capacities.
- Optimize capacities and responsibilities for the design and implementation of new energy efficiency measures.
- Better connection and coherence between policies and measures in different programmes
- Reduce the duration from programme development to the actual implementation

Close specific policy gaps

- Address the energy market to break monopolistic structures
- (Re-)establish and develop further successful energy efficiency programmes, based on the good experiences from the EEDSM
- Phase-out energy-wasting technologies, promote the most energy-efficient ones in order to stimulate innovation as well as to strengthen in particular also local manufacturers by creating ambitious product-specific policy packages in the general energy efficiency context
- Increase attractiveness of investments in energy efficiency with reduced payback periods
- Provide affordable and efficient appliances to the whole society

S&L case study: Recommendations for refrigeration appliances

The findings of the case study provide strong evidences for the recommendation that the S&L requirements for refrigerating appliances in South Africa should be revised as soon as possible to harness the available additional efficiency potential. Nowadays, an upward revision of the MEPS should also in particular not hold any considerable cost implications for manufacturers and consumers. The market obviously contains already a more than sufficient number of - also locally manufactured - efficient appliances that perform much better than required by the 2015 MEPS level.

To avoid that consumers and manufacturers lose faith in the reasonability and effectiveness of the entire S&L programme, similar considerations should be also made for all other product groups.

Furthermore, it is important that the DOE develops a reliable Measurement and Verification (M&V) scheme to ensure that at the end the market is actually compliant with the new requirements.

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How and When to Increase Alignment of Appliance Policies

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Abstract

Comparing energy performance requirements for appliances from country to country is difficult because of variations in product definitions, misaligned energy test procedures, and divergent efficiency metrics. This complex landscape can prevent policymakers from identifying or adopting global best practices in standards and labels (S&L). When S&L policies are comparable, policymakers can put policies in place more quickly and with fewer resources, while simultaneously removing trade barriers for highly energy-efficient products.

S&L policies are built on a series of technical foundations: product definitions, test procedures, efficiency metrics, and performance levels. Policymakers can increase alignment of product policies by improving the alignment of any of these building blocks.

Past research has shown that approximately 18 products are comparable. Such alignment is feasible for another 27 products, with the potential for more products to have components of the test procedure aligned.

But not every theoretical opportunity for alignment should be pursued. For globally traded products, alignment is beneficial to save regulators time and money, open markets for trade, and lower consumer costs. For products with more local specifications, alignment may not produce the same benefits since each government must ensure that policies apply to local conditions.

This paper discusses the specific opportunities for increased alignment of the building blocks that underlie product policy and present a framework for evaluating opportunities for greater alignment, using criteria to assess the suitability of such actions. This paper will also discuss potential paths forward to bring about that alignment through international standards bodies and international initiatives.

Introduction

Policymakers can compare national energy performance requirements and product coverage to those used in other countries around the world to better inform decisions about energy performance standards and energy labels (S&L). Often, these comparisons might lead to more stringent policies. However, the current inability to compare S&L among economies can lead regulators to set more conservative requirements than they might if they could easily translate or adapt other economies' more stringent policies in their own terms.

This paper builds on several pieces of foundational research initially carried out for CLASP and the SEAD initiative, bringing together findings from investigations into improving comparability of product policy and product benchmarking studies.[1] Synthesizing and adding to these findings, this paper provides examples of aligned policies, examples of why policies might not be aligned, and opportunities for further alignment.

[1] The authors would like to acknowledge the following individuals whose contributions and earlier research made this paper possible: Frank Klinckenberg, Mia Forbes Pirie, Jeremy Tait, Mark Ellis, Michael Scholand, Paul Waide, and Catriona McAlister.

Comparing energy performance requirements

Energy performance regulations are built on a series of interconnected parts, each of which define one building block for S&L and affect the comparability of these policies. Figure 1 sets out how various components of energy performance regulations interact. The figure reads from the bottom up, reflecting that the regulations that are most visible build on underlying, less visible parts.

In all economies, less than half of all regulations are fully aligned internationally. Full alignment requires first that product definitions and test procedures are aligned. In addition, a single efficiency metric must be able to define a globally acceptable way of describing what constitutes energy performance for a product. In other words, local usage characteristics must be comparable.

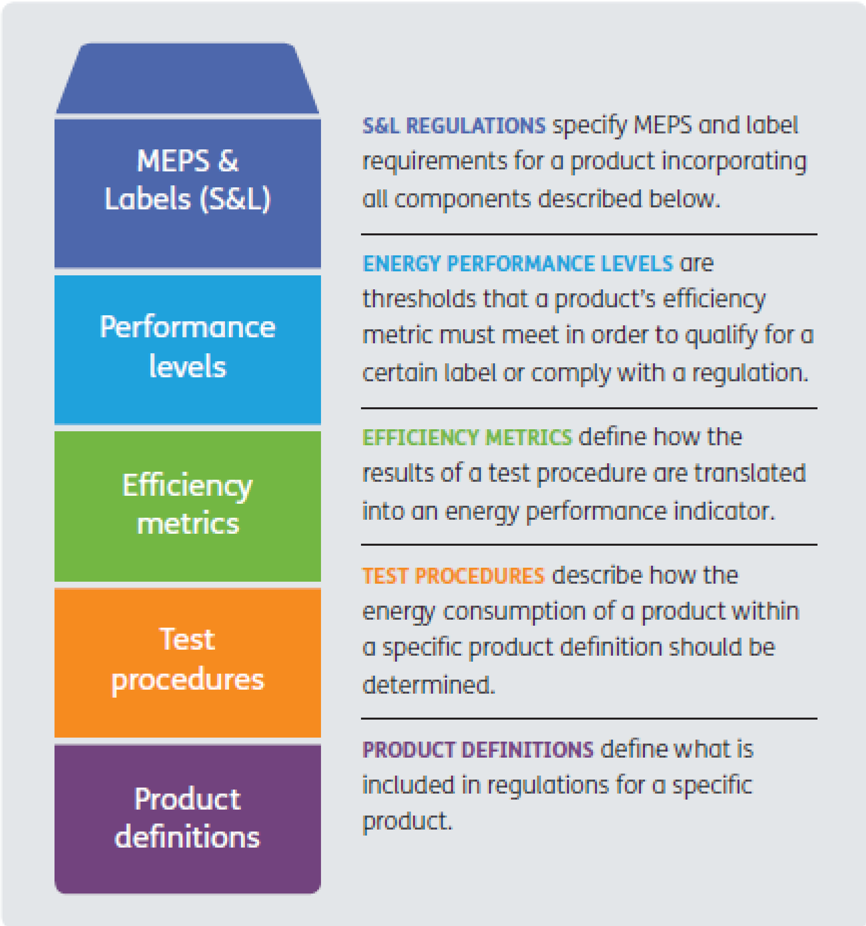

Figure 1: The building blocks of energy performance regulations

Efficiency metrics in general appear to be much harder to align than test procedures. Whereas international test procedures often seem to provide a suitable way of measuring energy consumption under standardized conditions, efficiency metrics are more often adapted to reflect different national circumstances such as climatic conditions or usage patterns. In fact, where there seems to be a movement towards using internationally aligned test procedures in all economies, efficiency metrics seem to be drifting further apart. A good example of this is in air conditioning, while virtually all economies have aligned to the same international test procedure for testing product performance, but then use quite different efficiency metrics to assess energy performance. In a way, this negates the progress being made in aligning test procedures for the purpose of product comparability. Also, it creates a barrier for the transfer of energy-efficient technologies between economies.

Aligned products

Based on the 2014 Improving Global Comparability study [1], there are 17 products that currently have alignment at least at the test procedure level (with some also having further alignment). Figure 2 shows these products and indicates for each the level of alignment beyond the test procedure.

Many products have an aligned test procedure but the alignment goes no further. At the next level of alignment, any product with an aligned efficiency metric also has aligned tiers and/or an aligned label. This shows that unaligned efficiency metrics are a significant barrier to having international performance tiers for a product.

Figure 2: Products with aligned test procedures

Examples of International Alignment

There are several products that have successfully moved towards regional or global alignment, and programs such as ENERGY STAR that have helped to achieve this.

Motors

The international IEC 60034-30 standard for single speed, three-phase induction motors establishes efficiency classes (or tiers) that can be adopted to meet the needs of an economy. The establishment of this standard also serves as a case study for how different standards-making organizations can come together to develop an internationally appropriate standard that meets the needs of policymakers and manufacturers.

Prior to the development of IEC 60034-30, there were effectively three test methods for electric motors used around the world. These standards were promulgated by the International Electrotechnical Commission (IEC), National Electrical Manufacturers Association (NEMA, in North America), and Japanese Industrial Standards (JIS). The IEC decided to revise its standard to bring it into line with the approach used in North America, which was generally regarded as technically superior but somewhat more expensive [2]. With significant international collaboration, the revised IEC test procedure was published in 2007. As part of the standards development process, the IEC also created efficiency classes or tiers that can be used as a ladder to help economies easily ratchet the stringency of standards. Tiers also make it easier to compare stringency across economies. While this is a successful example of global alignment, it was a slow and resource intensive process.

In addition, there remain small differences in the ways that these international tiers are adopted in national policies. In Australia, for example, the standard is set at slightly above an IE2 level – which is therefore not in alignment with the IEC tiers. This re-establishes trade barriers for these products, as manufacturers must ensure that products being sold into the Australian market meet the unaligned energy efficiency requirements.

External power supplies

External power supplies (EPSs) are used to power many types of consumer products, from aquarium pumps and handheld vacuums to laptop computers and mobile phones. California adopted the first mandatory energy performance requirements for EPSs in 2004, and several other governments followed suit in the decade that followed.

These regulations represented one of the first examples of the “horizontal approach” to controlling appliance energy consumption. That is, instead of creating a policy for a single end-use product, policymakers have addressed the energy consumption of many end-use products at once by addressing the energy performance of a component common to all of those products.

Test methods and efficiency metrics for EPSs are well aligned globally, with all known regulatory programs referencing the test method the US Environmental Protection Agency (EPA) developed for the ENERGY STAR Program. The test measures two quantities: average active-mode efficiency and the power consumption in no-load mode (when the EPS is plugged into mains but not connected to an end-use product). EPSs are unusual in that, in many jurisdictions, each unit must be marked with a Roman numeral indicating its energy performance level. These markings have also been aligned globally, and are defined in the International Efficiency Marking Protocol for EPSs, developed by the US EPA and now administered by the US Department of Energy (DOE) [3].

Most minimum energy performance standards (MEPS) in effect around the world today require EPSs to perform at either the Roman numeral IV or V level. The latter was the level required for ENERGY STAR qualification until the program for ESPs was discontinued in 2010. In February 2016, MEPS for most EPSs sold in the United States will become more stringent (Level VI). In addition, the scope of coverage will expand to include some uncommon product types that were not regulated previously, including EPSs with multiple simultaneous output voltages. To measure the energy performance of these multiple-voltage EPSs, DOE developed a new test method similar to the one used for single-voltage EPSs.

The more stringent MEPS (Level VI) will not apply to so-called “indirect operation” EPSs, which cannot operate an end-use product directly without the assistance of a battery. Indirect operation EPSs operate end-use products only indirectly, by providing power to charge a battery that, in turn, powers the end-use product. The US DOE made an exception for these EPSs due to this difference in functionality.

ENERGY STAR

The ENERGY STAR program was established in 1992 by the US EPA, and it is now supported by the US DOE. It is a voluntary endorsement label that recognizes products with superior energy performance. The program has subsequently been adopted by Australia, Canada, the EU, Japan, New Zealand, Switzerland, and Taiwan. This makes it easier for manufacturers to participate by testing products once and qualifying for an endorsement label in many different countries.

Organizations that sell ENERGY STAR qualified products in other countries must meet the same eligibility requirements as the US program [4].

Regional harmonization – North America

Canada, the US, and Mexico all have domestic appliance S&L programs and are parties to the North American Free Trade Agreement (NAFTA). NAFTA has made it easier to create markets for energy efficient products. In recognition of this, the North American Energy Working Group (NAEWG) was created as a forum for policymakers to improve energy cooperation. One of the areas of work is in appliance standards and labeling. Canada and the US both use the ENERGY STAR endorsement label, and most MEPS are harmonized, though implementation schedules may differ. There are several products with similar or identical MEPS and/or test procedures throughout North America, including refrigerators, freezers, air conditioners, heat pumps, and motors [5].

Why not to align?

Alignment is much easier for globally traded products, such as consumer electronics, which are often used in similar ways around the world. For products with more regional variation, it is not always practical or feasible to align products. This is especially true when climate conditions impact a product's operation or efficiency. Differences in culture or energy prices can also affect product usage patterns and lead to different energy and economic assessments from country to country.

Air conditioning product regulations use the same international test procedure for packaged products, though not for components, and vary greatly in the efficiency metrics used, leading to less alignment overall. This is in part because product performance can vary significantly in different climactic conditions for air-conditioning and refrigeration products. Countries may choose to use different testing conditions to properly reflect the local or regional climate and measure performance accordingly. This also makes it difficult to compare performance of products among economies because typically only the final performance metric—the energy efficiency ratio (EER) or seasonal energy efficiency ratio (SEER)—is available.

Cooking and space and water heating products show large regional differences in their design, usage, and performance characteristics. Regulations are typically built on regional test procedures and efficiency metrics, leading to virtually incomparable MEPS and labels for these products. It may be difficult to develop new, internationally aligned test procedures to improve comparability, given the substantial differences in product definitions and the overall approaches to regulating energy performance in the space and water heating product area.

Regional harmonization generally results in higher levels of efficiency, but not always. For example, in 2014 the Canadian government amended their MEPS for lighting to permit a less efficient form of incandescent halogen bulb that was permitted by the US regulation. Whenever possible, governments should avoid revising MEPS downward to align with an economy that has a less stringent standard than what is currently in place.

Framework for evaluating opportunities for increased alignment

The building blocks of energy performance regulations outlined in Figure 1 provide a framework for thinking about the possible levels of alignment for a product. However, the building blocks do not provide insight into what level of alignment might be optimal for a given product.

Figure 3 charts pathways for determining the appropriate level of alignment for products. Even though full alignment of efficiency metrics may not be practical or feasible, it is almost always possible to achieve at least some degree of alignment among product definitions or portions of test procedures.

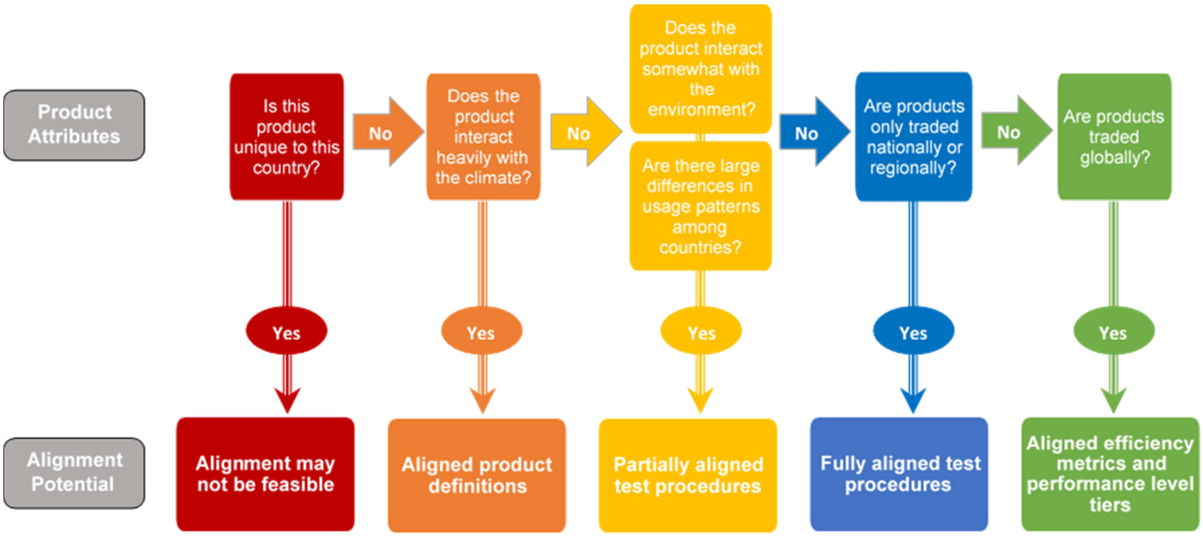

Figure 3: Framework for evaluating opportunities for increased alignment

Potential Paths Forward for Alignment

This section first presents general strategies that policymakers and other stakeholders can employ to improve alignment for energy using products. Later recommendations are made for paths to improve alignment for specific products including lighting, televisions, commercial refrigeration products, and distribution transformers.

Engagement with Standards Bodies

The IEC and the International Standards Organization (ISO) prepare and publish international standards for many energy consuming devices. Experts from industry, commerce, government, test and research labs, academia, and consumer groups participate in the development of IEC standards. Once a standard has been developed, it is often adopted or amended for use at the national level by member countries. There is recognition from the standards organization that they are a stakeholder in improving energy efficiency [6], but these organizations were not established to meet the needs of energy efficiency regulators; thus efficiency is not always prioritized when standards are being developed [7].

Recommendations

Resource constraints have limited the participation of efficiency stakeholders in the standards development process despite recognition of their value from both national policymakers and standards bodies. Both the ISO and the IEC have established advisory committees on energy efficiency and renewable energy. However, their principal purpose has been to identify gaps in International Standards and report suggestions to the technical management boards of their respective organizations, which in turn decide whether or not to communicate them to the committees that develop standards [8].

To leverage resources, policymakers can come together in international forums focused on end-use energy efficiency to discuss current research and strategies to engage with standards making organizations. Such international forums include the International Energy Agency's (IEA) cooperative program for Energy Efficiency End-Use Equipment (4E), the Clean Energy Ministerial's (CEM) Super-efficient Equipment and Appliance Deployment (SEAD) initiative, or the Asia-Pacific Economic Cooperation's (APEC) Expert Group on Energy Efficiency and Conservation (EGEE&C). If policymakers can create a coalition that presents comments to standards-making committees, they are more likely to have an influence on the standards-making process.

In the US, The American National Standards Institute (ANSI) has recently established the Energy Efficiency Standardization Coordination Collaborative (EESCC). The goal of the EESCC is to bring together experts from industry, federal agencies, standards-developing organizations, academia, and other stakeholders to discuss, coordinate and connect energy efficiency standardization activities [9].

The EESCC published a standardization roadmap [10] in 2014 which establishes a framework that industry, government, standards development organizations, and others in the US can use to improve energy and water efficiency in buildings. The next phase for the EESCC is to take action on the roadmap's recommendations, which includes influencing international standards discussions. The implementation of this roadmap is another timely opportunity for policymakers to engage in the standard development process.

Policymakers should focus their resources in participating in existing forums. They should also use the framework in Figure 3 to prioritize products to align.

Product-Specific Alignment Opportunities

Potential paths and alignment strategies for lighting, televisions, commercial refrigeration products, and distribution transformers are summarized in the following sections.

Directional lighting: Align cone shape

Australia, the EU, and the US have MEPS for directional lighting. These use comparable test procedures, but the US and Australia efficiency metrics cannot be compared with the EU efficiency metric.

The EU metric for directional lamps only considers light within a 90 or 120 degree cone (depending on lamp type), whereas most other economies (such as the US and Australia) consider the light in a 180 degree hemisphere. Converting between the EU "cone" approach and the more often-used "hemisphere" approach is difficult because the relationship between these methods is likely to vary for various lamp types. Developing a relationship would require in-depth examination of light distribution data from many lamps.

Therefore, even though the test method is the same – measure the light output from the lamp – the EU metric considers a more limited amount of the measured light (the light within the "cone") while other test methods measure a larger share of the light produced (the light within the "hemisphere").

Therefore, there is an opportunity to improve global comparability if the EU were to adopt the efficiency metric that considers the light in a 180 degree hemisphere.

All lighting: Agree generic performance levels for efficacy and quality characteristics

Lighting products are generally globally traded, including general service lamps (incandescent lamps, halogen lamps, compact fluorescent lamps (CFLs)), high-intensity discharge (HID) lamps and systems, linear fluorescent lamps and systems, and light-emitting diodes (LED) lamps and systems.[2]

Therefore, lighting products could become more globally aligned through international agreement of generic performance levels for efficacy. This concept is already in use for electric motors, in which the IEC defines international efficiency levels from which countries then choose among for adoption into national regulations.

Going one step further, these generic performance levels could also include aligned quality characteristics. Many voluntary lighting programs for highly-efficient products[3] already incorporate quality characteristics to ensure consumer satisfaction with the overall product. This, in turn, increases the likelihood that consumers will make an energy-efficient product choice in the future, rather than developing a distrust of new energy-efficient technologies.

[2] See, for example, Waide 2010. *Opportunities for Success and CO_2 Savings from Appliance Energy Efficiency Harmonization*. Available at: http://clasp.ngo/harmonization

[3] Examples include ENERGY STAR (lamps and luminaires), the IEA-4E Solid State Lighting Annex (http://ssl.iea-4e.org/), and the SEAD Global Efficiency Medal competition for efficient lighting products (http://superefficient.org/lightingawards).

Televisions: Agree on test method, including standardized test points and calculation metric for automatic brightness control (ABC)

Most countries that regulate the energy performance of televisions use a test method based on IEC 62087. The most notable exception is China, which uses different metrics and “out of box” testing conditions. Despite wide-spread adoption of IEC 62087, there is still room for improvement as there is significant variability in how the test standard is applied across economies.

SEAD conducted a study, in support of the Asia Pacific Economic Cooperation’s Collaborative Assessment of Standards and Testing (APEC-CAST) initiative, which identified areas where test methods diverged and which aspects would have the most significant impact on the measurement of energy use [11]. The findings are summarized in Figure 4.

Aspect of test method	Magnitude of impact
Luminance testing and measurement for on mode testing	LOW
Identifying ABC sensor location	LOW
Impact of TV stands in low illuminance on-mode-with-ABC testing	LOW
Sample preparation - inputs (RF vs HDMI)	LOW
Definitions and calculations relating to uncertainties	LOW
Equipment - Light source colour temperature and directionality	MEDIUM
Test video signals for new formats (UHD and 3D)	MEDIUM
Illuminance levels and calculations for on mode testing with ABC	HIGH
TV sample preparation for on mode testing (luminance setting)	HIGH
Dynamic broadcast-content video signal (need for revision)	HIGH

Figure 4: Test method aspects impacting the measurement of TV energy use

Differing policy approaches can introduce variance in the application of testing approaches. One example where there is opportunity to improve the comparability of test results is through harmonization of illuminance levels used for testing automatic brightness control (ABC). ABC reduces energy use by automatically adjusting the screen’s brightness in response to background lighting conditions. TVs can be tested with ABC enabled to incentivize the use of this feature. However, illuminance levels used for ABC testing should be representative of standard viewing conditions. The Department of Energy recently developed four illuminance levels that can be adapted for international use [12].

Refrigerated cabinets & display cabinets: Align regional test procedures and global product definitions

There are significant differences in test procedures, product definitions, and efficiency metrics for commercial refrigeration equipment (CRE). Some of these differences result from divergent markets, climate, and food safety requirements; these and other differences can be resolved or minimized by cooperation among stakeholders. There are many test procedures already in place and being used by industry, even though there are relatively few regulations when compared to other major domestic and commercial appliances.

CRE also presents a wide range of product types, some of which are not yet regulated at all, though regulation is spreading in scope and across more economies. This presents an opportunity for policymakers to identify areas for alignment now, before standards are in place. If there is international collaboration to develop robust test methods that are appropriate for different regions, this can reduce the burden and expense for countries that would like to regulate CRE but have not yet developed national policies.

One approach to improved alignment for commercial storage cabinets, commercial versions of domestic refrigerators and freezers, retail display cabinets, and vending machines is a staged approach that would identify short, medium, and long term opportunities to improve alignment [13]. This would give policymakers in different regions more time to adapt their standards to a more aligned approach. There is more variability between different regions and small variations in test methods and approaches within regions. The similarities within regions is to be expected because of similarities such as language, climate, and markets. Therefore, one focus should be to first eliminate or minimize the differences within the region, and then limit the variation between regions.

One useful step for clarity for refrigerated cabinets is to standardize product terminology and definitions that can cause ambiguity or confusion. For example, for refrigerated cabinets there are many different definitions for internal volume, which may correspond to gross, net, refrigerated, storage, or usable volume [14]. Standardizing definitions is relatively straightforward and an important step towards alignment. Cooperation with the IEC and ISO is essential as they both develop industry accepted definitions for products.

With standardized definitions in place, alignment of test methods can be improved. The following are some key technical aspects that should be considered [15], but this list is not exhaustive:

- ***Minimize differences in ambient test conditions.*** Some differences are appropriate to account for variations in climate. However, variations within regions could be minimized or eliminated and the number of regional variations could be reduced.
- ***Create a globally consistent set of storage temperature classes***, similar to what has been created for ice cream cold storage.
- ***Improve alignment of door opening regimes.*** All test methods specify a total number and duration of door openings over the test period, which can result in a 10-20% difference in the amount of energy consumed. It is reasonable for test methods to assume different door opening regimes for some different types of cabinets. However, the large variations in door opening regimes for the same type of cabinets between countries and regions appears unjustified.
- ***Lighting regimes*** can either be continuous (24 hours) or switched off for 12 hours out of a 24 hour test period. The impacts on energy consumption depend on cabinet size, lumens, and lighting technology.
- ***Test room configurations*** can vary or be inadequately specified. This factor has a relatively small impact on energy consumption, but there is little justification for variations.

Distribution Transformers: Align test methods and adopt international efficiency tiers

Distribution transformers—which convert power from high voltage on a power line to low voltage for use in buildings—are an integral part of every electricity distribution network around the world. In 2013, the SEAD Initiative reviewed existing test methods for distribution transformers and made recommendations for improved alignment and the adoption of efficiency tiers [16].

Most economies use IEC 60076 as the basis for test standards for distribution transformers. The exception is the US and Canadian standards which are based on IEEE C57.12.00 and NEMA TP-2. The IEC and IEEE/NEMA standards cannot be directly compared because the methodology for measuring no-load and load losses differs. Both of these standards have been used reliably by industry for many years and so alignment may not be feasible in the near term [17]. However, alignment is feasible in the long run, and policymakers should work together in international forums, including the IEC, to support the adoption of the SEAD efficiency tiers. These recommendations follow a similar approach to that which was developed for motors.

The following considerations must be addressed as part of an alignment strategy:[4]

- ***Select performance metric**.* There are two methodologies used for calculating energy performance for transformers: percent efficiency and maximum losses. It is recommended that regulators use percent efficiency as the performance metric; maximum losses limits variety in the market, restricts the design and material options available to manufacturers, and can result in utilities purchasing suboptimal transformers for a customer's requirement.
- ***Define efficiency.*** The IEC test method measures efficiency using inputs power while for the IEEE, the equation is based on output power.
- ***Select a loading point.*** If percent efficiency is selected as the metric, then it is necessary to select a level at which efficiency will be reported.
- ***Standards for accurate measurements.*** Most regulations calculate efficiencies to the one hundredth of a percent, thus the measurements that feed into this calculation must also be made with sufficient accuracy to enable power efficiencies to be determined with accuracy to 0.01%.

Key findings and Next Steps

In all economies, less than half of all regulations are fully aligned internationally. Full alignment includes product definitions, test procedures, and efficiency metrics. Efficiency metrics in general appear to be much harder to align than test procedures. Products with an aligned efficiency metric also have aligned tiers and/or labels, showing that the unaligned efficiency metrics are a significant barrier to comparable international product performance tiers.

The IEC has successfully set international tiers for motor efficiency, but the pathway to get there was slow and resource intensive. Also, some countries still set their standards at slightly different levels than the IEC tiers.

External power supplies are well-aligned internationally, using the International Efficiency Marking Protocol for EPSs that was developed by the US EPA for the ENERGY STAR program and is now administered by the US DOE.

For some products, differences in climate conditions, culture or energy prices can impact their operation, usage patterns, and efficiency. This can lead to different energy and economic assessments from country to country, and in some cases it does not make sense for these products to be fully aligned. However, even though full alignment of efficiency metrics may not be practical or feasible, it is almost always possible to achieve at least some degree of alignment among product definitions or portions of test procedures.

To improve alignment of product policy, policymakers should focus their resources in participating in existing forums that can engage the relevant IEC and ISO committees in discussions focused on energy efficiency. Policymakers should also use the framework presented in Figure 3 to prioritize products to align.

Product specific recommendations:

- Directional lighting: The EU can align to the more often-used efficiency metric that considers all light emitted in a 180 degree hemisphere.
- All lighting: Agree to generic performance levels for efficacy and quality characteristics
- Televisions: Agree on test method, including standardized test points and calculation metric for automatic brightness control (ABC)
- Refrigerated cabinets & display cabinets: Align regional test procedures and global product definitions

[4] For a more detailed technical explanation see the SEAD Distribution Transformers Test Method Review Report, available at reference [16].

- Distribution Transformers: Align test methods and adopt international efficiency tiers

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Innovative SME Energy Efficiency Financing For Controls-Based Solutions

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Abstract

Small and medium commercial enterprises ("SMEs") represent a largely untapped energy efficiency opportunity in the United States. Enabling the widespread implementation of energy efficiency measures for SMEs – defined here as commercial facilities less than or equal to 50,000 square feet – represents a major opportunity for energy efficiency service providers due to its aggregate scale; SMEs comprise 49.4% of all commercial floor space and 94% of all commercial buildings in the United States.
As the cost of energy efficiency hardware continues to decline and building automation reaches into smaller buildings, there are revenue opportunities created that have previously been unavailable to the SME market. In addtion, utilities and ISOs start to accept smaller volumes of flexible demand response and offer a wider choice of energy-efficiency programs, allowing also residential customers to benefit from a steadily growing range of rebates.

NorthWrite Inc., in conjunction with performance- based financing by the Joule ERA Fund, has designed an energy efficiency implementation program, *Agile Volt*, specifically for the SME market. By installing low cost building controls and rooftop HVAC unit retrofits, NorthWrite guarantees a fixed rate of energy savings to its customers over a short capital recovery period (typically 1-5%) and then a larger 10%+ savings thereafter, without upfront costs to the customer. By offering its program at no upfront cost to the customer, and leveraging third-party energy performance insurance, NorthWrite is addressing the three most consistent barriers to energy efficiency: *Lack of capital, high investment return criteria, and uncertainty of savings*.

Energy efficiency opportunity for small and medium commercial buildings

The United States is a nation of small commercial buildings. Small and medium commercial enterprises ("SMEs"), defined here as commercial buildings less than or equal to 50,000 square feet represent 49.4% of all commercial floor space and 94% of all commercial buildings in the United States [1].

Table 1. 2012 CBECS Preliminary Results

Building Floor Space (square feet)	Percentage of Total Buildings	Percentage of Total Floor Space
1,001 to 5,000	49.9%	9.2%
5,001 to 10,000	21.1%	10.2%
10,001 to 25,000	15.9%	16.3%
25,001 to 50,000	6.0%	13.8%
50,001 to 100,000	3.6%	16.0%
100,001 to 200,000	1.6%	14.2&
200,001 to 500,000	0.7%	12.3%
Over 500,000	0.1%	8.1%

Source: own research

The most optimistic energy efficiency study identifies potential energy efficiency savings of 9.1 quadrillion BTUs as compared to a Business As Usual (BAU) scenario in 2020, a reduction of 23% below current annual electricity consumption; an energy efficiency potential of 1,080 TWh for the year 2020. End-use efficiency potential distribution among the major sectors is as follows: residential (35%), industrial (40%), commercial (25%) [2]. If we assume that the energy efficiency potential in commercial buildings is spread equally, then buildings 50,000 square feet and under have a potential of: 133 TWh for the year 2020.

Barriers to energy efficiency

Despite the fact that energy productivity of the U.S. economy, defined as the ratio of energy use per unit of GDP, has roughly doubled over the past 40 years, there remains a major unmet potential [3]. In the United States, the three most consistent barriers to energy efficiency implementation are firms' lack of upfront capital for efficiency projects, uncertainty about the savings achievable, and a perceived low return on efficiency investments [4, 5, 6].

Table 2. 2011-2013 Johnson Controls BPI Survey Results – Common Energy Efficiency Barriers

	2011	2012	2013
Capital Availability	38%	37%	31%
Payback/ROI	21%	21%	20%
Savings Uncertainty	10%	12%	17%

Source: own research

In order to better contextualize the value of solutions being implemented by energy efficiency providers today, it serves to describe the three most consistent barriers in greater detail:

Upfront Capital

Particularly in the SME sector, capital is scarce. What capital exists is generally used for core business use, even it could be invested at a higher rate of return in energy efficiency projects.

Uncertainty of Savings

Many owner/operators are dissuaded from pursuing energy efficiency because they lack certainty that the savings that they are paying for will actual be realized. Energy efficiency contracts are divided into two major types: deemed savings and measured savings. The majority of contracts provide for deemed savings, i.e. the contractor and customer agree to a certain level of savings that will be achieved by the project, with payment not tied to actual measured energy savings. One of the major benefits of a deemed savings project is the ease with which the customer can understand the benefits. By their nature, deemed savings projects do not require the added expense of metering for verification to demonstrate savings. Particularly when pursuing smaller projects, the costs and logistics of a rigorous measurement and verification (M&V) to date, has been prohibitive. However, when customers opt for deemed savings contracts, they also lose the information exchange that may be important in reinforcing the value of the energy savings provided.

Due to the nature of deemed contracts, they are most popular for lighting projects, which produce the most reliably predictable savings. Heating, ventilation, and air-conditioning (HVAC) projects, because they are dependent on the weather, building envelope characteristics and building system operations, generally require measurement and verification to be marketable to customers. This creates challenges and tremendous opportunity since the costs of measurement and cloud-based communications continues to trend down.

Return on Investment

Investments made on non-core business practices are generally regarded as requiring a quick payback time in order to receive consideration. Studies have indicated that the average maximum payback for an energy efficiency project varied slightly among industrial customers (2.7 years), commercial customer (2.9 years), and institutional customers (4.3 years)[7]. The short payback time requirements observed in the market limit the types of energy efficiency measures that are being pursued despite compelling return on investment for more comprehensive retrofits.

Business models to address energy efficiency barriers

An opportunity exists today for the emergence of a new performance-based service approach to the SME market. The new energy services business can be uniquely positioned to capture savings, capitalize on smart grid revenues and create compelling investment opportunities.

The performance-based service leverages experienced M&V analytics using the same cloud- based communications platform to transmit data on energy use as it occurs, a user interface that seamlessly presents this information to the consumer, incentives provided for energy efficiency projects (e.g. utility), market revenues earned from wholesale markets, and third-party investment sources (e.g. Joule Energy Reduction Assets Fund). Combining these elements creates the potential for a scalable business model for energy services company.

There is an argument to be made that these characteristics are crucial to addressing the as-yet untapped SME market. According to the McKinsey Global Institute, investments in energy productivity could achieve an average internal rate of return of 17% and generate energy savings up to $900 billion annually by 2020 [8]. Revenues from Demand Response (“DR”) in the US alone are estimated at greater than $3 billion, and growing at 20% annually [9]. Proprietors, franchise owners, regional retail chains, property managers – all facing the common challenge of deploying their scarce capital to their core business, are passing on energy upgrade opportunities, even when presented with very attractive paybacks.

Conventional financing can fill some of the gaps. However, the installer is faced with locating a financier or leasing company that will underwrite the customer, assuming the customer is willing to take on the risk that the measure(s) will achieve the savings and a clear reporting of the results over the financing term.

The new service presents the customer with a confirmation of energy saved through its IPMVP compliant M&V, actively manages installed HVAC and lighting controls via it's cloud-based interface to achieve schedule savings, and captures a small quantities of fast-response demand response for additional revenue to the customer. Combined, these elements produce opportunity that has attracted third-party capital sources such as Joule Assets' ERA Fund.

The new energy service model enables additional service provision in the form of commodity procurement, by presenting energy retailers with an energy efficient customer with the capability to shed load during peak events – an attribute retailers highly value. Alternatively, the new business can position itself as a partner to a retailer as part of a customer acquisition and retention strategy.

Businesses that can leverage their technical capacity with today's low cost communications and technology applications stand to gain by moving quickly into this vast and untapped market.

Third-Party Financing

To date, the majority of energy efficiency financing has been delivered by Energy Service Companies (ESCOs) providing energy efficiency retrofit projects. Many transmission and distribution utilities also offer low or no-cost energy efficiency financing to their customers. As of 2012, approximately 15% of the global commercial building energy efficiency retrofit market was paid via financial instruments [10].

Volumes can be dedicated to the explanation of the ever-expanding list of energy efficiency financing options, but for the purposes of this paper we only discuss the benefits and limitations of two forms: equipment leasing and energy service agreements for SMEs.

Equipment Leasing

Energy efficient equipment leasing enables SME owner/operators to gain the benefits of energy efficiency at comparatively low interest rates. In this model, SME owner/operators pay fixed monthly payments and keep 100% of the savings generated. Equipment leasing benefits from its relative simplicity, but remains an on-balance sheet obligation for end users.

Energy Services Agreements

An increasing number of financial entities and energy service companies have begun to offer energy service agreements (ESAs) to the SME sector. ESAs differ most fundamentally from equipment leases in that the project implementer retains ownership and operation of the energy efficient equipment installed and provides the resulting savings as a monthly service fee to the SME owner/operator. In turn, the SME owner/operator "purchases" energy savings like they do electricity, as a monthly operational payment. Contracts are generally designed so that the energy service fee is less than the expected monthly energy cost savings, providing a positive cash flow to the SME owner/operator.

Due to their structure, ESAs can be treated as off- balance sheet from the perspective of the SME owner/operator, enabling a larger market for financed energy efficiency equipment. While capital scarcity ranks as the greatest barrier to energy efficiency, many firms are not willing to take on debt in order to capture energy efficiency savings, even if it would create a positive monthly cash flow. Because of this reality, off-balance sheet financing mechanisms like the ESA serve to broaden the potential implementation of energy efficiency in the SME sector.

Energy Savings Performance Insurance

Energy Performance Insurance (EPI) has the potential to play a significant role in the development of the energy efficiency market for SMEs.

Through EPI Policies, SME project developers can provide investment grade performance guarantees to their project beneficiaries and financiers. This provides developers and financiers access to some of the project finance structures, accounting treatments, and project origination techniques that have historically been exclusive to the investment grade energy services companies.

By agreeing to pay for shortfalls in projected project performance, EPI insurers allow project stakeholders to confidently and efficiently underwrite a project's revenue by assessing the strength of the underlying insurer's credit rating and policy coverage. This allows an EE Project to be treated much more like an annuity, or other commoditized financial asset, and for the EE Financier to further homogenize their underwriting processes and portfolio.

Project Developers use EPI to reduce their sales process to a review of their project's insured performance. This translates the project's value into a simplified financial decision for the project beneficiary's decision makers including mortgage holders and tenants.

Moreover, EPI removes the need for a project beneficiary or financier to engage a third-party engineer, which can be a significant obstacle to project origination and funding. EPI performs the same role as a third-party engineer without the upfront cost but with a financial guarantee.

Project beneficiaries and financiers can potentially increase their returns by having their performance guarantees tied to the cost of the insurance instead of the project's profit margins, as the investment grade energy services companies have historically done. This is possible because EPI allows developers to transfer the financial liabilities generated by their guarantees to the insurer's balance sheet.
As the SME Market has grown so has the EPI Marketplace. In just the last 12 months, more than 4 international insurance companies have entered the EPI Marketplace. Joule Assets is at the forefront of this market development through its ERA Fund and is working to support a liquid, efficient, and competitive EPI marketplace that benefits all EE market stakeholders.

Available market revenues

Facilities that take advantage of energy efficiency upgrades stand to benefit from multiple revenue earning opportunities, in addition to utility cost reductions.

Many grid-managed markets offer a wide variety load management products. A subset of these load management markets are permanent load reduction markets in which an energy efficiency project that results in permanent energy reduction can qualify for "capacity" payments. "Capacity" payments are set by auctions based on how much a project is expected to reduce the load during its peak hour(s) (thereby reducing the need for additional generation). Another subset of load management products is demand response in which a controls-based ECM reduces load on demand for a short duration based on a signal received from the grid (either directly or indirectly).

Some load management markets retain a set price over time for products. Ontario, for example, sets an annual price that varies depending on location. Other markets (e.g., NY, New England, Mid- Atlantic) hold auctions that commit the bidder to offer LM for a specific time (e.g., coming month, or year). Load management markets often hold auctions that cover commitments three and four years in advance. In New England, a permanent load reduction market sets its "Forward Capacity" prices several years in advance through auctions. Other market clearing prices shift radically from day-to-day and from hour-to-hour.

Investment in energy efficiency in open markets provide substantial opportunities because:
(i) Electricity rules and regulations are determined through a more open process than in vertically integrated markets;
(ii) There are many more counter-parties in an open market than in a fully regulated market, and many more prospective business partners;
(iii) Market participants including end-users are generally more informed and active;
(iv) Because Regional Transmission Organizations operated by Independent System Operators (ISOs) generally encourage competition, and it is less expensive to reduce consumption than to construct

new power plants, ISO markets have developed a broad suite of permanent load reduction and demand response products; and

(v) In ISO markets, there are often four to eight wholesale grid products, each offering different investment and return opportunities to facilities offering permanent load reduction and demand response, depending on their advance notice and duration characteristics and whether the resources can be aggregated with others.

Rebates and Incentives

Utilities and state energy agencies in the United States spent more than $2.4 billion on customer incentive payments for energy efficiency in 2012 [11]. Incentives for energy efficiency can pay up to 70% of the costs of a project; utilizing rebates and incentives is critical to the project economics for many SME efficiency deals

Demand Response

Supply and demand must always be in balance to ensure grid reliability. With the expansion of intermittent power supplies such as wind and solar (that vary depending upon time, date and weather conditions) there is a greater need for mechanisms that keep the grid in balance and stable.

In the last ten years, grid operators have realized that, as flexible as generators are in adjusting production, consumers are even more flexible in adjusting consumption. Since a reduced kilowatt of consumption has roughly the same effect in keeping the grid in balance as an increased kilowatt of production, grid operators now allow consumers to sell their willingness to reduce consumption in the same market that generators sell their willingness to increase supply.

Energy supply (and prices) will, for a given market, depend upon the level of commitments from end-users who agree to manage their load, the number of load management projects, and the tightening or relaxation of eligibility rules. These variables create risks, opportunities, price discovery and/or uncertainty that an investment (in controls-based ECMs) in this space can benefit from.

Demand for load management products is driven primarily by how much end-users are expected to consume at peak, anticipated constraints on the electricity transmission system (e.g. intermittent renewables) and on ISO (or grid) policies. The introduction of demand response sourced from the SME market presents compelling opportunities (revenues from wholesale market participation) and challenges (scale, M&V). To date, incumbent market participants typically struggle to incorporate small loads into aggregated portfolios. Historically, their portfolios were (and continue to be) made up of non-automated demand response. The new generation of participating load is automated and generally will come in smaller increments. This opens the door for new business models for those firms able to adapt.

As intermittent resources such as wind and solar continue to gain acceptance and adoption across the US grid, ISOs are focusing more on the value of fast response resources, otherwise referred to as "Ancillary Services", to meet short-notice resource needs.

The investment in controls-based solutions can often enable responsive load that is well suited to deliver Ancillary Services and therefore receive compensation. When ECMs are automated, additional revenue streams are accessible and therefore, informed investment with active oversight can be profitably deployed.

The increasing availability of cloud-based communications for data transfer and signaling is resulting in smaller and smaller increments of load shedding capability being enabled (e.g. less than 10 kW per facility). These smaller increments are, in several ways, superior to the larger loads currently participating in utility programs and ISO markets: (i) they can receive a signal directly from the grid manager without requiring an intermediary as the required equipment is installed at the time of the EE upgrade; (ii) enablement is automated with no requirement for manual intervention or decision- making; (iii) due to automation and signaling reception, the ability to participate in Ancillary Services markets; (iv) delivery in close to real- time of DR performance is provided via revenue grade metering and cloud-based communications, a key M&V requirement; and (v) customer opt-out capability is built in. These features allows the enabled DR facility to optimize its third-party relationships for aggregation and settlement (e.g. with curtailment service providers, utilities and ISOs) therefore capturing maximum value.

Acceptance by utilities and ISOs of small DR resources is evolving. As automation becomes more of a standard requirement to participate, there is an acknowledgement that small DR increments may be suitable resources. To date, the vast majority of DR resources currently participating in the utility and ISO markets are not automated, requiring emails, phone calls, texts to deliver curtailment events to participants. However, going forward, the vast majority of utility program RFPs and ISO programs are targeting automated DR enablement as a condition to participation.

With smaller increments of load shedding capabilities being accepted by utilities and ISOs, also the residential sector comes into focus. The bundling of energy efficiency hardware with electricity supply contracts has seen a lot of success in the US, most prominently with the deployment of Nest thermostats. Nest enables residential customers to save money on their electricity bills through automatic optimization of HVAC scheduling. In addition, customers benefit from a more intelligable consumption feedback and – depending on the utility – from additional rebates, which allow them to recuperate installation costs in less than two years. As customers benefit from a steadily growing range of choices in terms of energy-efficiency rebates, the energy efficiency industry is set to radically change [12].

Case study – Northwrite's Agile Volt

Energy efficiency providers have begun to address the SME market with a controls-based program. One of these early entrants, NorthWrite Inc., has developed their *Agile Volt* service, designed specifically to address the needs of commercial buildings smaller than 50,000 square feet. Smaller commercial buildings often lack building management systems, a key component in capturing efficiency opportunities for HVAC systems.

Agile Volt Service - Technology

The Agile Volt service provides for low-cost building controls (wireless sensors, dedicated packaged unit controllers, lighting controls and communicating thermostats). NorthWrite utilizes its "active oversight" of the system to not only save HVAC energy, but also enable participation in demand response markets, earning additional revenue for the customer in the process.

Although no reliable nationwide estimates are available, numerous studies over the past decade have shown as much as 30% or more of the energy is unnecessarily wasted in commercial buildings [13, 14]. This is a direct result of improper control (set-points, schedules, etc.) and the inability to diagnose and correct operational problems in a timely manner. A number of studies have documented the potential savings from enhanced building O&M. Savings noted in these studies varies from 10% to 60%. Many researchers believe that 10% to 30% of heating, cooling, HVAC auxiliary, refrigeration and lighting energy consumption can be saved by actively managing these systems, and proactively monitoring energy use.

The Agile Volt service is leveraging its extensive energy efficiency, hardware and software expertise and existing products and platforms to create a system that addresses these very problems. The energy savings of Agile Volt customers is achieved through a combination of improved/more consistent schedule and set-point control, fault detection/diagnostics, and simple ESM retrofits (e.g. lighting controls, dedicated RTU controls, etc.)

Agile Volt Program – Contract Type

The Agile Volt program is particularly noteworthy in the way that it is financed. NorthWrite is providing its Agile Volt system to customers free of upfront charges. During the initial term of the agreement, NorthWrite takes on the utility bill payment obligation and charges its customers a fixed percentage of their of baseline energy costs (previous 12-months total utility spend). Actual savings achieved varies by customer and the systems installed. The difference between the actual savings achieved and the guarantee savings provides funding to pay for the capital and services provided [15].

On an annual basis, the customer is provided with additional demand response revenue earned throughout the preceding 12 months. After the initial term is completed, the customer receives all energy efficiency benefits net of a nominal monthly service charge to pay for continuing oversight of the system. An example of the anticipated cumulative cash flow and monthly savings percentage for an early Agile Volt customer is presented below:

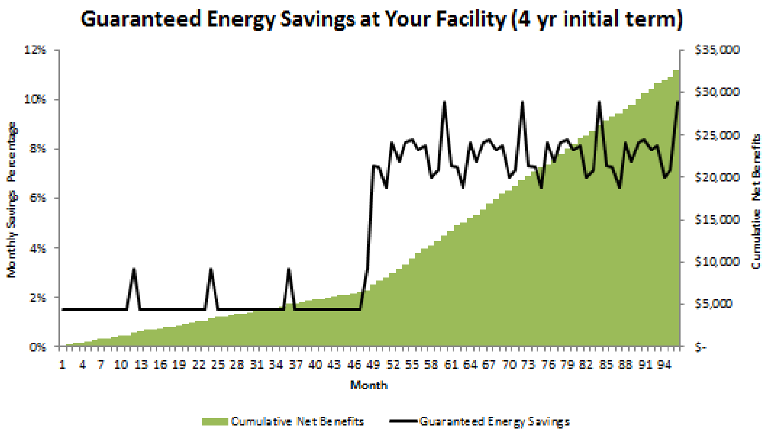

Figure 1. Agile Volt customer benefits

Conclusion

Technology improvements in the building energy management industry, combined with an emerging business model that incorporates the benefits of cloud-based energy oversight, control, M&V and reporting creates a powerful investment opportunity that (i) delivers real and consistent savings to the facility; (ii) accesses market revenues and incentives in a way previously not possible; (iii) recurring revenue model for ESCOs in a vast untapped market; and (iv) reduces our dependence on carbon-based fuels for energy delivery and grid reliability.

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A step-by-step transition towards the management of electricity consumption in households

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Abstract

Starting from the assumption that a well-informed consumer is one of the key drivers for a change towards a more energy efficient society the paper begins with an outline of recent experience, results and lessons learnt from two European consumer-oriented projects: Energy Neighbourhoods$_2$ and Yearly Appliance Energy Costs Indication. It is obvious that there is a limit of achievable savings (both financial and “environmental”) only through behavioural changes. The next step is choosing more efficient and financially long-term beneficial appliances when replacing the old ones.

The paper shows positive results from targeted approach and guidance of consumers both when a change in life style and a change in purchasing patterns are concerned. A transformation of consumers’ perception of the relation between lifestyle, purchasing decisions and related costs is outlined, as well as development of retailers’ approach towards shaping motivation of buyers to choose appliances from the top efficiency range.

In practice, however, and as explained in the paper, the point is not in reduction of electricity but energy consumption and related costs, where electricity does have a more and more visible share in the final score but also helps improve the energy balance and cut the overall operational costs.

Based on these observations and collected data a speculative concluding look into the near future is made: how can the aforementioned trends influence the share of electricity consumption in the residential sector and how do they support the transition towards approaching nearly zero-energy building (nZEB) standards.

1. Introduction

With the economic situation becoming strained many households seek ways to reduce monthly expenses. To some extent this can be done by a change in life style, which need not reflect in decline of occupant comfort. Even though the price of electricity may still be low at the moment (the average electricity price for Slovenian households with an annual consumption from 2.500 to < 5.000 kWh being 162,95 €/MWh with all taxes included [1]), noticeable savings can be achieved if patterns of use of various domestic appliances are adapted and unnecessary electricity consumption is avoided. There are many related hints and tips available and published even in popular press, but very often a possibility of a direct exchange of experience among consumers and a possibility of a clear overview of monthly consumption and observation of trends are the real and inspiring motivators and vital drivers for a change. The ability and opportunity to compare is important also when making purchasing decisions for new appliances. Not only the initial cost and technical characteristics, but also long-term costs of operation can be a decisive factor to a conscious consumer.

On the other hand, national Action plans for nearly-zero energy building (nZEB) promote technologies where in some cases (additional) electricity consumption is inevitable (example: AP nZEB Slovenia [2]). Through recent years we have been facing a significant increase of new buildings and renovations done to high energy efficiency standards. Some of these may consume more electricity than an average household does. The reason lies not in bad building design or in an inadequate conception of the term “energy efficiency”. This is simply because the majority of integrated building systems use electricity for their operation (e.g. warm air heating system, radiative heating system, heat pump as part of a central heating and cooling system, mechanical ventilation with heat recovery, etc.).

Electricity consumption accounts for a significant share of the operating costs in non-residential buildings (office and other commercial buildings, service establishments, industry, etc.). Such trends are expected to progress to a certain amount to residential building stock as energy efficiency requirements are becoming more and more stringent. In other words, the reason why the share of electricity use for operation of household appliances and devices will become more and more noticeable lies within requirements for reduced energy use for the operation of critical/significant building systems such as space heating and cooling, domestic hot water production, and ventilation.

Implementation of modern measures should aim towards bringing positive results in increasing the level of energy efficiency and share of renewable energy sources in the building sector. This can only happen, however, if all relevant stakeholders are included in planning and construction processes. Only an integrated energy design makes it feasible to verify every important building parameter.

Building legislation, related trends and modern technologies are changing. The number of households with devices, appliances and systems using electricity is increasing. For these reasons we may reasonably doubt some forecasts predicting the downwards trend of electricity use in households.

2. Energy Consumption in Slovenian Households

The energy consumption in Slovenian households had fluctuations in the decade 2000-2010. The initial increase in consumption in the years 2000-2003 was followed by a decrease in years 2004-2007, but there was another rise in years 2007-2010. Overall, the energy consumption in households was almost 15 % higher at the end of the decade than at the beginning. But when climate corrections were taken into account, it remained almost at the same level.

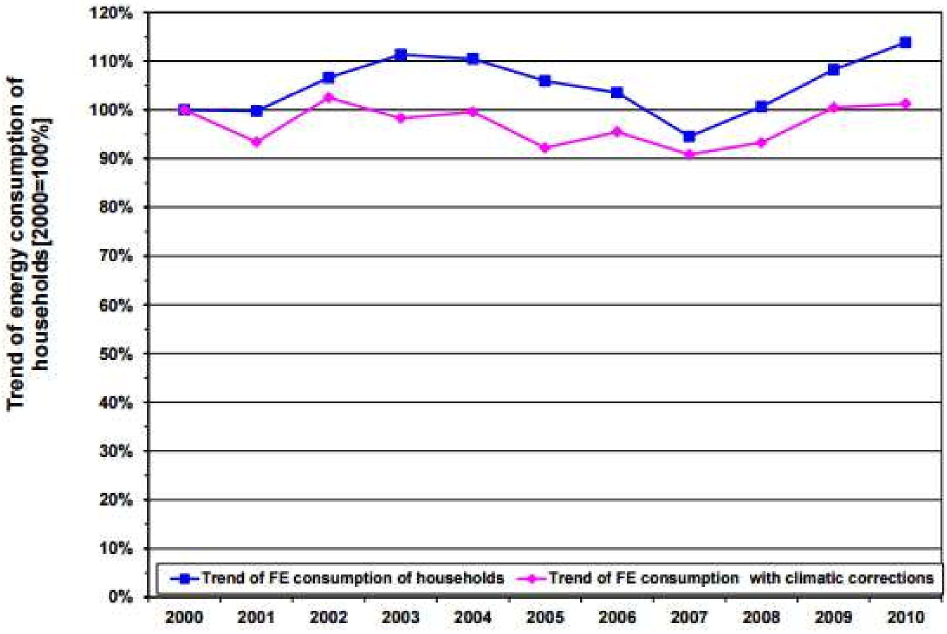

Figure 1: Trend of final energy consumption of household in Slovenia in comparison to the baseline year of 2000 (2000-2010) [3]

The largest share of final energy consumption was used for space heating. There was also a slight increase in consumption of electricity used for household appliances.

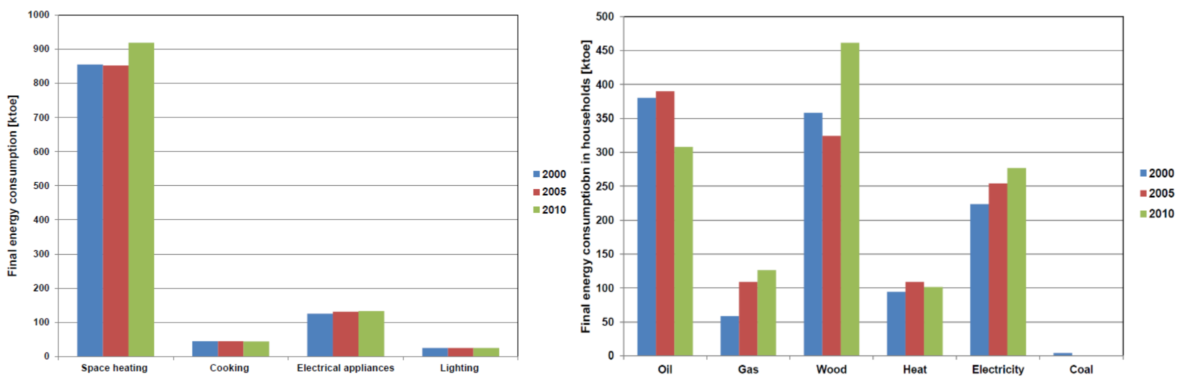

Figure 2: Final energy consumption and energy carriers in Slovenian households [3]

A breakdown of electricity consumption by end use showed that in 2013 large household appliances (refrigeration and freezing appliances, washing and drying machines, and dishwashers) consumed 820 GWh (around 25 %) of electricity. For water heating 634 GWh (almost 20 %) and for space heating and cooling 473 GWh (almost 15 %) of electricity was consumed. For TV sets and personal computers 320 GWh (almost 10 %), for cooking 272 GWh (around 8 %) and for lighting 236 GWh (around 7 %) of electricity was consumed. [4]

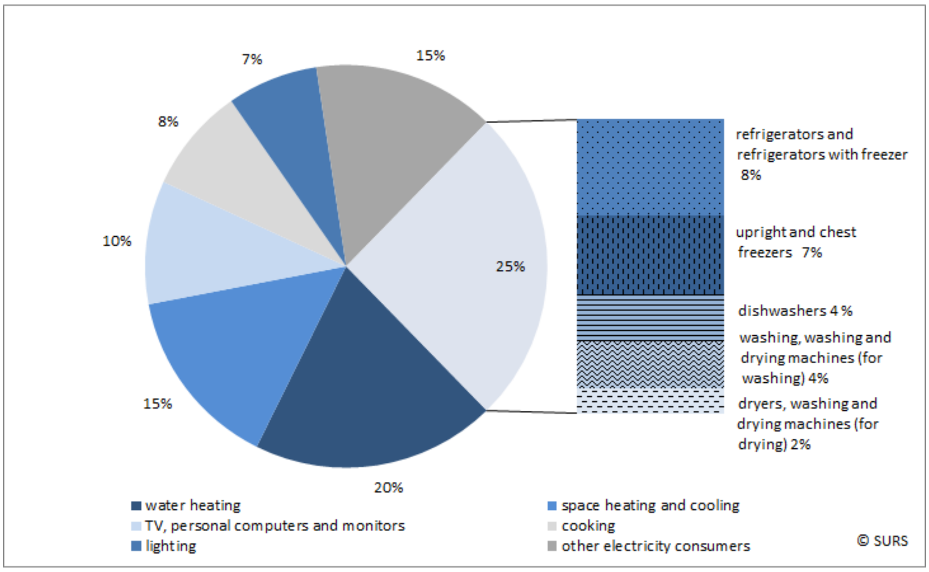

Figure 3: Electricity consumption, households, Slovenia, 2013 [4]

The trend of specific unit consumption of large electrical appliances in households shows that they are generally becoming more and more energy efficient with only one exception, the television sets. On the other hand, washing machines notably improved their energy efficiency for almost 40 %.

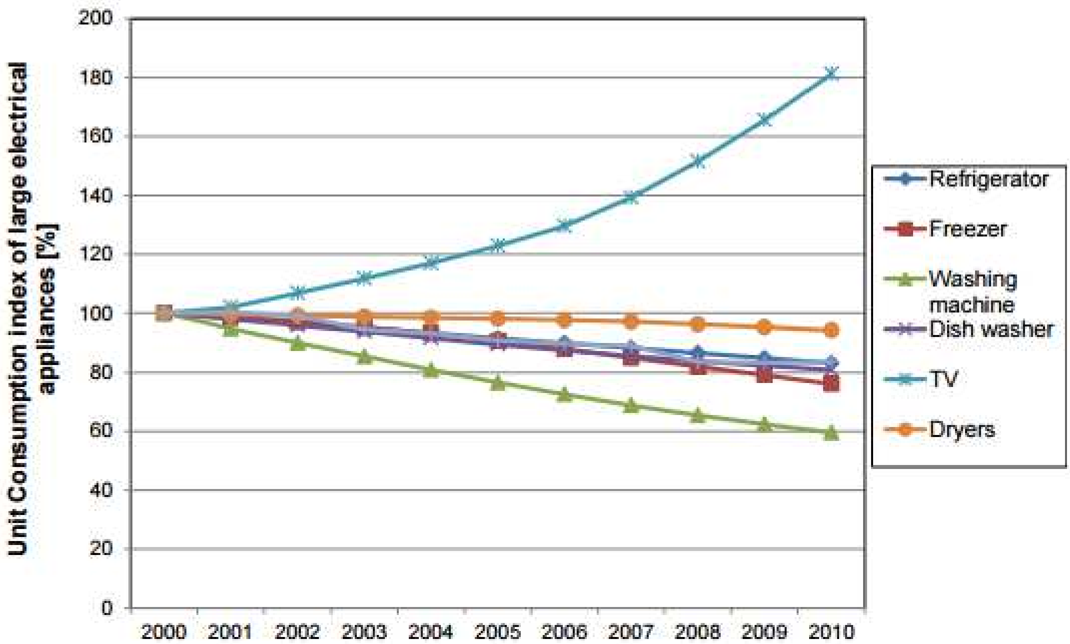

Figure 4: Trend of electricity consumption per appliance group in Slovenia in comparison to the baseline year of 2000 [3]

The specific unit consumption of large electrical appliances in households should be reducing, but that is not the case in Slovenia. The statistical data show that over the past 15 years an upward trend in total number of households has exceeded the population growth. Between 1961 and 2002 the number of households increased by nearly 50 %, while the population increased by a mere 25 %. Between 2003 and 2007 the number of households increased by 4,5 % and the population growth was 1,5 %. In 2007, there were 745.000 households in Slovenia [5]. At first glance one would conclude that electricity consumption will increase, as every household has at least basic electrical appliances, e.g. a refrigerator, washing machine and small household appliances; some households also have a dishwasher, heat pump and ventilation system. However, the result of both trends is that the energy consumption for electrical appliances in Slovenian households is not increasing much - the growing number of households is compensated by more and more energy efficient appliances in place.

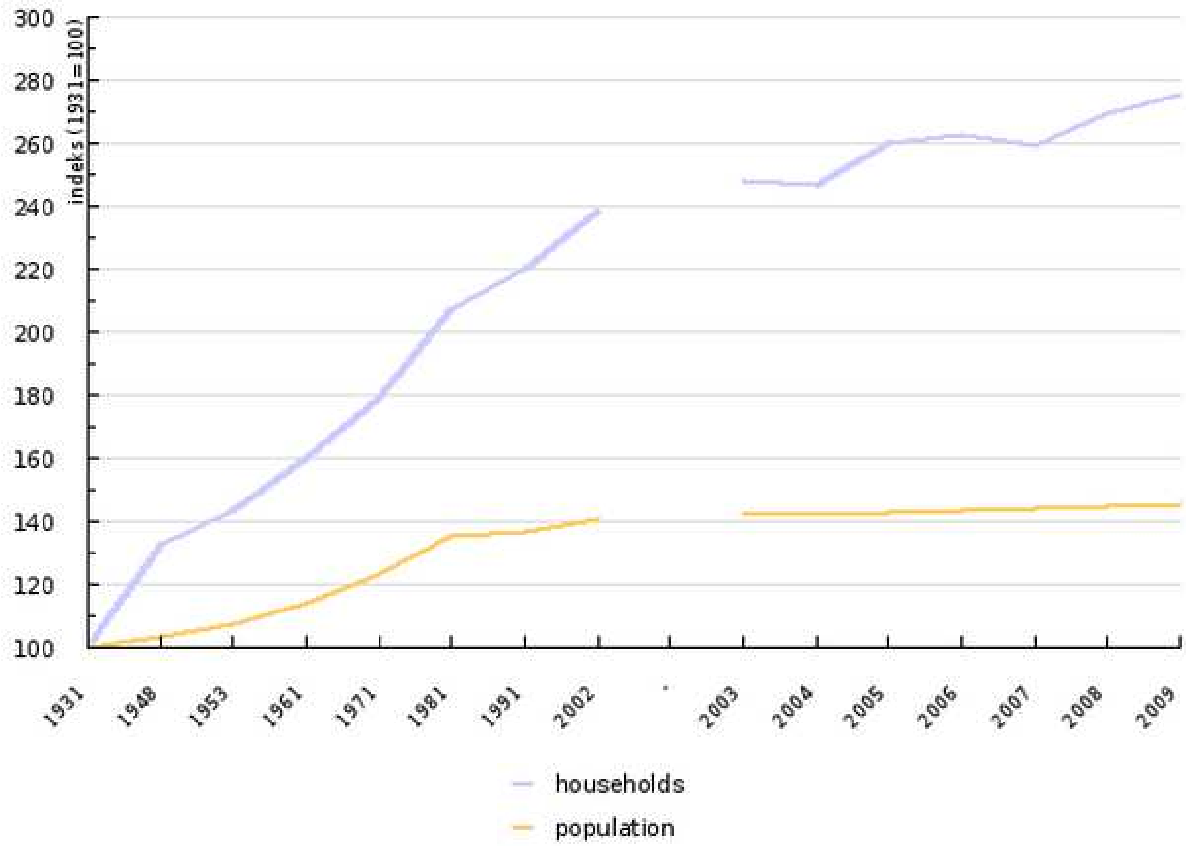

Figure 5: The growth index in the number of households and population in Slovenia in comparison to the baseline year of 1931 [5]

Note: The chart is intentionally divided into two parts, because the data are taken from two different sources: Population Census 1931-2002, Statistical Office of the Republic of Slovenia; since 2003: EUROSTAT 2009.

3. Slovenian households with energy efficient lifestyles

The cheapest way of achieving energy savings at home is through organizational measures. Numerous good practices from real-life projects exist showing a significant impact of behavioural changes on energy consumption in private households. A related case study was conducted within the Energy Neighbourhoods$_2$ project (acronym: EN$_2$) from the Intelligent Energy Europe programme [6]. The project and its results are briefly presented in this chapter.

Households from Slovenia and fifteen other European countries participated at an international energy saving competition. The stakeholders were invited to form groups of minimum five and maximum twelve households. The teams called “neighbourhoods” took on an energy saving challenge. The concept behind it was for each neighbourhood to try to save as much energy as possible compared to the previous (baseline) period simply by changing the way they did things around the home and without their living comfort being lowered. As it was a behavioural change-only project there were no investments into higher energy efficiency allowed.

Group members selected one person within each neighbourhood and assigned him or her the role of an “Energy master”. This individual acted as a coordinator for the group and received specific training to help the team to achieve energy savings. The teams recorded energy consumption continuously over four-month periods in two competing campaigns: 1.12.2011 – 31.3.2012 and 1.12.2012 – 31.3.2013.

The households had recorded and entered data on energy use into a simple online calculation tool during both competition periods. The online tool was easy to use so they were able to enter their meter readings and understand the results they got back in a very simple way. All key parameters that could have a significant impact on the actual results were carefully taken into account, e.g. the baseline period duration and past energy data input; regular energy consumption and its share per evaluated building system; the temperature difference between the baseline and monitoring period.

The calculation tool was vital to help participants visualize their energy use and the energy savings they were making. Additional help was also provided with a set of tailor-made materials. These support tools gave participants directions on how to walk the path to energy saving greatness:

- Energy Neighbourhood handbook: A step-by-step guide through the competition with detailed instructions on how to use the energy saving calculator on the website.
- Do it yourself Home Energy Check: A Checklist to help identify energy hungry appliances and practices in their home.
- Readings Record Card: An aide-memoire for all the meter readings taken during the competition.
- Top Tips: Every 2 weeks a set of top tips was sent out with yet more ideas on how to save energy around the home, often focusing on seasonal topics.

This pan-European campaign ended on 31.3.2013 and short after its finish winning teams from the two campaigns were announced. Best teams from each participating country were awarded with a free of charge trip to Brussels where they attended a special prize-giving ceremony.

The results and responses from participating households from Slovenia showed that they had obtained good insight in how much energy they use and how they use it. Ninety-five households participated in both campaigns; forty-five of them competed in both individual seasons. Sixty-five households managed to reduce their electricity bills. If these households continue with the same patterns of consumption they will save more than 28.000 kWh of electricity in one year. On an average, one household reduced its electricity consumption for more than 10%, which accounts for more than 400 kWh.

Just this simple competition was enough to teach people what a unit of energy is and help them work out how much energy they actually consume in their home. Most importantly, it was made clear how this relates to their energy consuming practices and the type and use of appliances. The result is a far more energy conscious consumer who can add energy literacy to the own list of life skills.

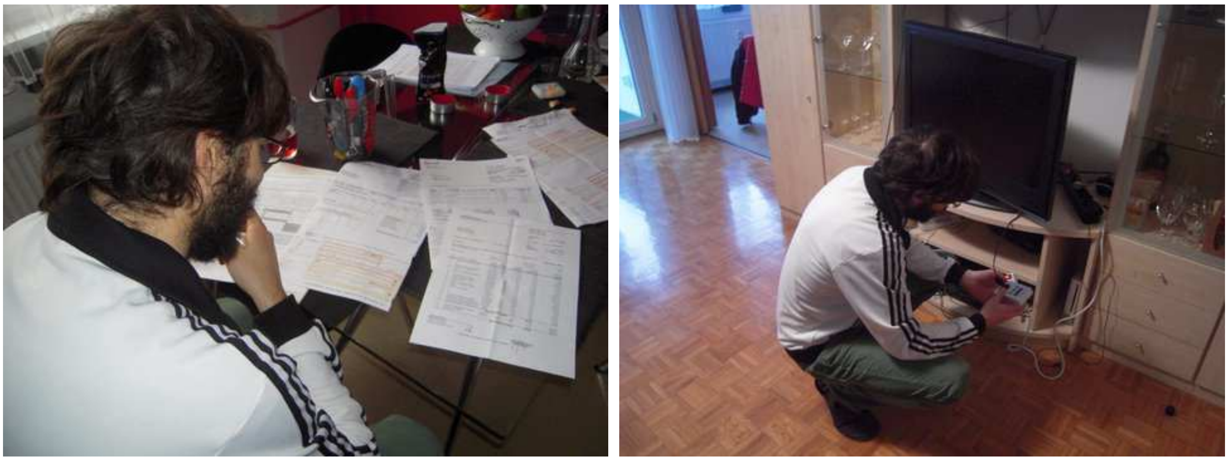

Figure 6: Utility bill audit and measurements of television electricity use in standby mode (Source: [ZRMK archive])

4. Consumer Behaviour in Slovenia

When organizational measures can no longer save energy it is time to make further moves. One of the most logical next steps is to buy appliances with higher energy efficiency.

When making decisions about a purchase of a new appliance for many customers the lowest price is no longer the main criterion. More and more attention is focused on cost-effectiveness in the long run. Therefore many are interested in the return rate of their investment: how long will it take the energy savings to cover the cost difference between a more expensive but more efficient and a cheaper but less efficient appliance.

One of the tools that help consumers making decisions is an indicator of the annual energy cost. This voluntary indicator is located next to the energy label on a household appliance and can be found in stores managed by three different Slovenian retailers. The indicator expresses annual cost (in euros) of the energy consumed for operation of a particular appliance. The value refers to the consumption of electricity. In the case of dishwashers and washing machines the indicator also includes the annual cost of water. The calculation of costs follows a common method based on data from the energy label and average national electricity and water prices.

The idea of cost indicators arose in the context of the YAECI project (Yearly Appliance Energy Cost Indication, co-financed by Intelligent Energy Europe programme) [7]. The main objective of the project was to show annual operating costs of the most common household appliances and devices on the spot in stores. This measure supports sales of the best energy classes and contributes to the actualization of the European objectives to improve energy efficiency. Moreover, such additional information at the point of sale helps consumers to transform sometimes abstract energy figures expressed in kWh into something much more familiar to everyone: money.

Figure 7: Display of the annual energy cost indicators on household appliances (Source: [ZRMK archive])

5. Bringing it together and to a higher level

The supposition is that an average private electricity consumer has more and more information at hand allowing him or her to better plan own patterns of use of appliances, make more sound purchasing decisions and manage own expenses more effectively. An informed customer is usually a more demanding customer, and a demanding customer puts certain pressure onto manufacturers and retailers. This bottom-up evolvement slowly influences the overall market and gives an important signal to other market players to shift focus to more efficient products.

Although the above statement may seem exaggerated it had happened before in another market segment. In late 1990s state subsidies for energy efficient windows and glazing were available to Slovenian households in case of purchase of highly efficient products. Up to that time little attention was being paid to energy characteristics and related operational costs, and the market was saturated with low quality products. Then, customers started demanding and buying only top range products. It was not only the subsidies that did the job, but also accompanying information and awareness-raising campaigns. In only one or two years the supply changed dramatically, following the developing demand for new products.

In case of home appliances consuming electricity there are indeed no subsidies available at the moment, which would bring an additional (and so very attractive) push forward to household owners and buyers to rethink their usual practice. On the other hand, the awareness level among general public has risen visibly through the last two decades, and the inter-relations among energy consumption, operational costs, and even wider environmental impacts are now observed more carefully.

6. Fitting into the wider picture and trends

There is no need to repeat here the well-known energy-related targets and goals until 2020 and beyond, be it on the national or EU level. The overall energy consumption must and will be reduced. As mentioned in the introductory chapter there may be a reversed picture when electricity is concerned. The quality of life is viewed also through the measures and elements improving living comfort and saving time for various activities.

Electrical appliances, from large ones to gadgets, are a part of this. Although contemporary products have significantly improved energy efficiency their number is increasing, and so are the frequency and intensity of their use. It is true that we normally do not replace products in perfect working condition just because of their less favourable energy characteristics. This would in most cases not be economically feasible. The makeover of the stock is thus gradual, usually connected to technical lifetime reached or exceeded. In statistical terms this is also a less predictable process, especially in the sense of quantification of energy usage.

In addition, energy consumption is reduced not only by measures on the building thermal envelope, but more and more by an introduction of technical, control and monitoring systems, which require electricity for operation. Another point of interest and a factor less tangible is for instance electricity use for heating. For about three decades electricity was not allowed as the only source of heating energy in Slovenia. With the Energy Law from 2014 [8] this ban has been lifted, also to allow for use of advanced low temperature electrical heating systems and devices suitable for low-energy and nZEB standards. It is not possible yet to predict how this change will influence the share of electricity use in the overall energy use framework.

7. Is prevailing use of electricity in buildings sustainable?

National emission factors for an individual fuel, stated by the Republic of Slovenia in its most recent national greenhouse gas records submitted to the Secretariat of the United Nations Framework Convention on Climate Change published on the website of the Environmental Agency of the Republic of Slovenia [9], show that electricity has the greatest impact on the environment among all energy carriers. Is a building sustainable and environmentally friendly if it uses electricity as the sole energy source for operation of building systems?

The Slovenian regulation on efficient use of energy in buildings [10] sets the minimum requirements for new buildings and major renovations with the following indicators:

- The maximum U values for the building envelope, building components and windows.
- The obligatory share of renewable energy sources (RES) in the final energy use.
- The maximum primary energy use.

The case study below shows a comparison of different building systems that are in accordance with the national legislation (primary energy and renewable energy sources criteria). The building envelope and mechanical ventilation with heat recovery system remain unchanged in all variants and are determined by the minimum regulatory requirements.

The example shows a single-family house study of building energy supply. The scenarios differ in three heating systems variants that use various sources of energy with different proportions of RES:

1. Biomass heating system, radiators.
2. Heat pump (air-to-water), floor heating.
3. Natural gas heating system (condensing boiler) in combination with solar panels (minimum requirement for the use of RES in residential buildings), radiators.

Figure 8: The analysed single-family house in Križe, Slovenia (Source: [ZRMK archive])

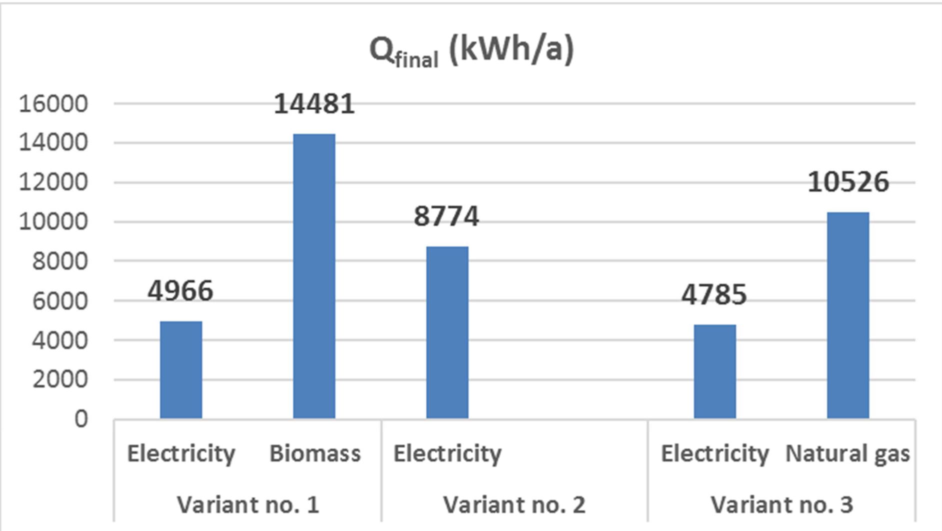

Figure 9: Final energy consumption determined according to the national calculation methodology, based on the national method [10], EN ISO 13790 (Energy performance of buildings Calculation of energy use for space heating and cooling [11], and CEN EPBD standards

Table 1: Share of RES in the final energy use and CO_2 emissions

Variant no. 1		**Variant no. 2**		**Variant no. 3**	
RES (%)	CO_2 (kg/a)	RES (%)	CO_2 (kg/a)	RES (%)	CO_2 (kg/a)
75	16	50	29	17	29

The calculations show the best results in final energy consumption for the variant no. 2. The advantage of heat pumps is in moderate investment costs and in a continuous supply of electricity. The environmental impact in operation is similar to the scenario with the condensing gas boiler (variant no. 3) due to a higher efficiency of the system. The variant no. 1 is the most expensive in terms of initial investments. On the other hand, the biomass heating system uses the cheapest and most environmentally friendly source of energy for its operation.

All scenarios considered coincide with current legislation and modern sustainability guidelines. A wider use of electricity in heating systems can be expected due to the advanced heat pump technologies and their compliance with the requirements of the latest trends.

8. Conclusion

The growth of electricity use in the Slovenian residential sector is largely driven by the increasing number of households and use of electricity in building systems. Heating and hot water production are already dominant segments, but its additional increase will be inevitable due to the modern guidelines of sustainable construction. In cases where buildings mostly operate on electricity, their energy balance will become more transparent to users.

A more conscious management of energy accounting in households will provide a good basis to induce more energy efficient user behaviour. This will allow users to have a better insight into the effects of their organizational and other measures to increase energy efficiency.

The major appliances in homes - refrigerators, washing machines, dishwashers - account for a substantial share of monthly utility bills. Since modern homes must meet national energy efficiency standards, more emphasis will be visible and given to the electricity use for the operation of appliances and devices.

The more information will be given to consumers in the purchasing process of construction products, household appliances, lighting, technical systems, etc., the higher standards of energy efficiency will be achieved. Labelling programs aim at simplifying the process of identifying and purchasing energy efficient products which may cost more than standard models, but will pay back through lower energy bills.

A decline in electricity consumption in the residential sector is not likely to be expected. The electricity use will still be slowly increasing, eventually to settle at a certain higher level in the future, but its use will certainly help improve energy efficiency and use of renewable energy sources in this area and will not negatively affect the overall energy performance of buildings.

Investigating the trends on the national level and comparing them with the ones from the wider geographical area we see that the principles for reduction of electricity use, “reduce the use” or “reduce by replacement”, are being overrun on the cumulative level by the growing number of households and electricity consuming appliances and systems. As shown, this does not imply a negative final impact. It shall be noted that here we did not address the question of environmental indicators related to the origin of electricity in use, which may be from renewables, nuclear power, fossil fuels, or a mix of various sources.

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Tapping into energy and CO2 savings in EU households through the use of building automation technology – a policy pathway to savings

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Abstract

This paper reports key findings from a recent study into the potential for building automated control systems (BACs) and related automated technology to save energy in Europe's households and from a follow-up analysis of policy options. The techno-economic savings potentials from greater adoption of simple but effective building automated control systems in Europe's homes is found to be ~1 357 Mtoe from 2015 to 2035; however, the analysis shows there are a variety of barriers that are inhibiting the realisation of this potential. This paper presents a portfolio of policy options designed to overcome these barriers including:

- building capacity among building energy controls service providers and engineers
- strengthening interoperability and standardisation
- raising market awareness and strengthening education along the supply chain
- developing targeted financial incentive mechanisms designed to stimulate supply and demand of quality BAC products and services at as fast a scale as can reasonably be sustained
- certification and accreditation of suppliers, designers and installers
- mandatory requirements regarding labelling, minimum performance and installed systems

Much of the above could be implemented by making use of and adapting existing policy levers, in the EPBD (Directive 2010/31/EU) and Energy Efficiency Directive (Directive 2012/27/EU), and practical routes for doing this are explored within the paper. Prior to this, however, the paper considers what policy actions designed to trigger savings from better use of BACs could be implemented through the Ecodesign Directive, which is of immediate relevance given the ongoing Ecodesign planning review.

The savings analysis estimates that full implementation of these measures would result in 498 Mtoe of cumulative energy savings and avoid 1.3 gigatonnes of CO_2 emissions from 2015 to 2035 for EU residential buildings compared to current trends. Some €95 billion of extra investments in BACs and related services would be needed to deliver these savings, at an average of €5 billion per year. Large as these incremental investments are, they are almost six times less than the value of the resulting savings in energy bills, which total €562 billion over the period, at an average of €28.1 billion per year.

Glossary

BACS = building automated controls

BAT = building automated technology

EED = Energy Efficiency Directive

EEO = Energy Efficiency Obligation

ELD = Energy Labelling Directive

EPBD = Energy Performance in Buildings Directive

EPC = Energy Performance Certificate

HEMS = home energy management system

MS = (EU) Member State

HVAC = heating ventilation and air conditioning

NEEAPS = National Energy Efficiency Action Plans

Introduction

Buildings are widely reported to consume 40% of all energy in Europe [1] of which residential buildings account for 71% of final energy consumption [2]. In recent years, they have received increasing attention by policymakers seeking means to reduce the energy requirements of the building stock. Much of the effort to date has focused on new construction and major alterations, tightening building regulations to improve the efficiency of the building fabric and the installed equipment. Legislation has also promoted renovation of the existing building stock, greater use of renewable energy, and the disclosure of energy performance (mostly modelled, not actual) via energy rating and labelling schemes. Very little attention has been paid to building automated technology and control systems, which is surprising given their potential to reduce building energy consumption substantially and rapidly, at relatively modest cost.

This paper presents the findings for the residential sector of an analysis commissioned by the European Copper Institute (ECI) to examine the potential of building energy controls to accelerate energy savings [2] and complements this with a more recent, as yet unpublished, analysis of the policies that could promote greater savings through building automated technology and controls. It demonstrates the undoubted potential of building automated technology (BAT) and controls (BACS) to save large amounts of energy, with a technical and economic potential of some 23% across the residential building stock, amounting to 9% of all EU energy use [2]. However, it also cautions that to achieve this potential will require considerable improvements, not just in the technology (which already has great capabilities and is advancing rapidly) but in its effective design and application in buildings. Too often, BAT/HEMS installations do not fulfil their promise, distancing users from the systems with which they need to interact. Effective deployment of BAT/HEMS in the residential sector is therefore as much about the calibre of professional services in designing, applying, integrating, installing, commissioning, and handing over BAT/HEMS as it is about the products themselves. This need for greatly improved deployment in both qualitative and quantitative terms is reflected in the recommendations in this paper.

Current technologies and barriers to their implementation

Modern building automated technology (BAT) brings the electromechanical hardware of sensors, actuators and thermostats together with ICT hardware such as controllers/outstations, programmers and central facilities such as personal computers (PCs) and data displays. Collectively these can be combined with appropriate software to provide home energy management systems (HEMS) for residential buildings; however, it is important to understand that varying degrees of integration and sophistication are used and that the most appropriate system will vary in response to the building and usage characteristics.

The HEMS market can be considered to be comprised of stand-alone systems, networked systems and in-home displays.

- Stand-alone systems will typically consist of sensors and an information display that communicates with the sensors and utility meters. More advanced systems will have a central management system that collects consumption data from multiple devices and enables their control via standard consumer IT devices, such as smartphones or PCs.
- Networked systems establish communication between HEMS and energy utilities and are designed to enable demand response, i.e. to enable consumers to modify demand in response to time-dynamic tariffs. Networked systems are more costly to install and require consumer willingness to cooperate with the utility to modify their energy use. While they have been trialled, they are currently much less common than stand-alone systems.

- In-home display systems simply display energy meter data in real time to show how much energy is being used in the home. They neither directly control the energy-using equipment nor display information on specific end uses, but they do allow consumers to attempt to correlate the consumption profile with the operation of equipment and thence make manual adjustments to equipment to regulate energy use.

In-home displays are thus a means for increasing information on home energy use; however, they are not really a building automated control technology as they do not control the energy-using equipment. Therefore, they are not really considered to be a full BAT system/HEMS.

The control provided by stand-alone and networked HEMS are supported by intelligent device controllers such as smart thermostats, also known as ‘programmable communicating thermostats’, which have the ability to send and receive information wirelessly. These are an example of building automated technology and should not be confused with the HEMS that can be used to program them from a central location according to a schedule. These smart thermostats can not only be remotely controlled via consumer ICT devices but can also be set to provide operation on demand, i.e. when a space is occupied. Similarly, plant such as boilers, air conditioning and ventilation systems can be managed by device-level controllers that connect and communicate via a standards communications technology and protocol. The more advanced HEMS will also have sensors/controllers that allow sensing, monitoring and control of other equipment besides HVAC, including lighting and appliances, but this functionality comes at an extra cost and its economic viability is less proven.

The savings potential from the use of these systems (controls and automated technology) comes about by avoiding heating or lighting in unoccupied rooms and by better scheduling of when heating starts and stops to take account of occupancy overlaid against the thermal response of the building. Building automated technology systems can be quite simple, for example in homes they principally concern ensuring that as many spaces as relevant have their own programmed thermostatic actuator capable of controlling the heat flow to that space (usually by being integrated into the heat emitter). Programming can be done centrally through a HEMS often via wireless communication. The more spaces where the demand for heat delivery is sensed and controlled individually rather than as an aggregate the greater the savings. The same systems should also employ optimum start/stop and weather sensing to avoid heating coming on unnecessarily early or staying on too long by learning the thermal response of each room.

There is a plethora of elements and systems configurations on the market with different levels of functionality and which use differing operational software, communication technology and protocols. The sheer variety of solutions that are available is one of the biggest hurdles to both broader adoption and improved implementation because the value proposition from automated controls becomes blurred between competing claims and is adversely affected by implementation problems that are exacerbated by insufficient standardisation. In part this diversity and complexity is also driven by the broader pace of developments in ICT more generally and simply reflects the widening array of possibilities that have become available as technology evolves; however, there is an ongoing tension between the emergence of new solutions and the need to standardise to facilitate deployment at scale and reduce implementation difficulties. In the residential sector there is also a need for solutions to require the minimum disturbance of inhabitants during installation and for aesthetic sympathy with the décor in the home.

Market trends

The European automated controls market has held steady throughout Europe’s current economic recession, despite the fact that the natural installation opportunities are strongly related to new-build and renovation events, which are sensitive to broader economic trends. This is because renovation and renewal rates have increased slightly as building owners have become more sensitised to (i) the value of energy savings, (ii) the arrival of new technologies with additional value, and (iii) the impact of more proactive broader public policy measures, such as the EU’s Energy Performance of Buildings Directive (EPBD), all of which have helped stimulate demand. Given these trends, penetration of HEMS is projected to rise from 2% of homes today to 40% by 2034 without additional policy intervention. This, rate of penetration may seem to be addressing the problem but in fact will leave a large proportion of the savings potentials untapped. Not least because the default system in most EU national markets is to have a single thermostat in the home used to control all the heat emitters, thus very often when the building is occupied and heating is required in one room all heat emitters are activated.

Savings potentials

Three scenarios were developed in the ECI report [2] to assess the potential for additional energy savings:

- the **Reference Scenario**, which assumes a continuation of current trends regarding the adoption and installation of BAT/HEMS in the residential sector, with no significant improvement in installation and management procedures
- the **Optimal Scenario**, which assumes an optimal level of installation and operation of BAT/HEMS from a user cost-effectiveness perspective
- the **Recommended Action Scenario**, which assumes that the recommended actions outlined in the ECI report and elaborated upon here are implemented and that the BAT/HEMS are procured, installed and operated accordingly.

These scenarios were simulated for the European residential building stock in a purpose-built building energy stock model to estimate the expected impacts on building energy use and costs. The magnitude of savings achieved per installation obviously depends on the baseline level of controls, the functional sophistication of the new installation and the nature of the building and energy services being controlled. In a typical EU household where heating is the main source of energy use a sophisticated automation and control installation will bring in features such activation of each heat emitter only in response to demand rather than by default (usually based on room occupancy scheduling with manual override capability), optimum start functionality (which takes into account the heating time lag of the space to optimise the timing for when heating is initiated and deactivated), and weather compensation (that also helps to optimise how much heat should be is delivered to a space at what time). Collectively these control measures save considerable amounts of heating energy compared to a whole house thermostat and thermostatic radiator valve controls arrangement, which would be a typical default setting (see [2] for more details).

At the macro pan-EU scale the potential energy savings from greater and more effective deployment of building automated controls and technology is vast. The total techno-economic optimal savings potential as expressed through the Optimal Scenario is estimated to reach 23.4% of all residential building energy consumption by 2029 declining slowly thereafter; however, this is predicated on a rational and perfectly functioning market without serious constraints to effective service delivery. Under the Optimum Scenario the penetration of BAT/HEMS reaches 100% of homes in 2028. A more realistic depiction of the potential to deliver additional savings beyond the Reference Scenario (business-as-usual case) is offered by the Recommended Action Scenario. In this case, savings ramp up progressively over the scenario period to reach 11.3% of the Reference Scenario energy consumption by 2035 (Figure 1). This is associated with a steady but accelerated rate of penetration of BAT/HEMS rising from 20% of homes in 2020 to 83% in 2035.

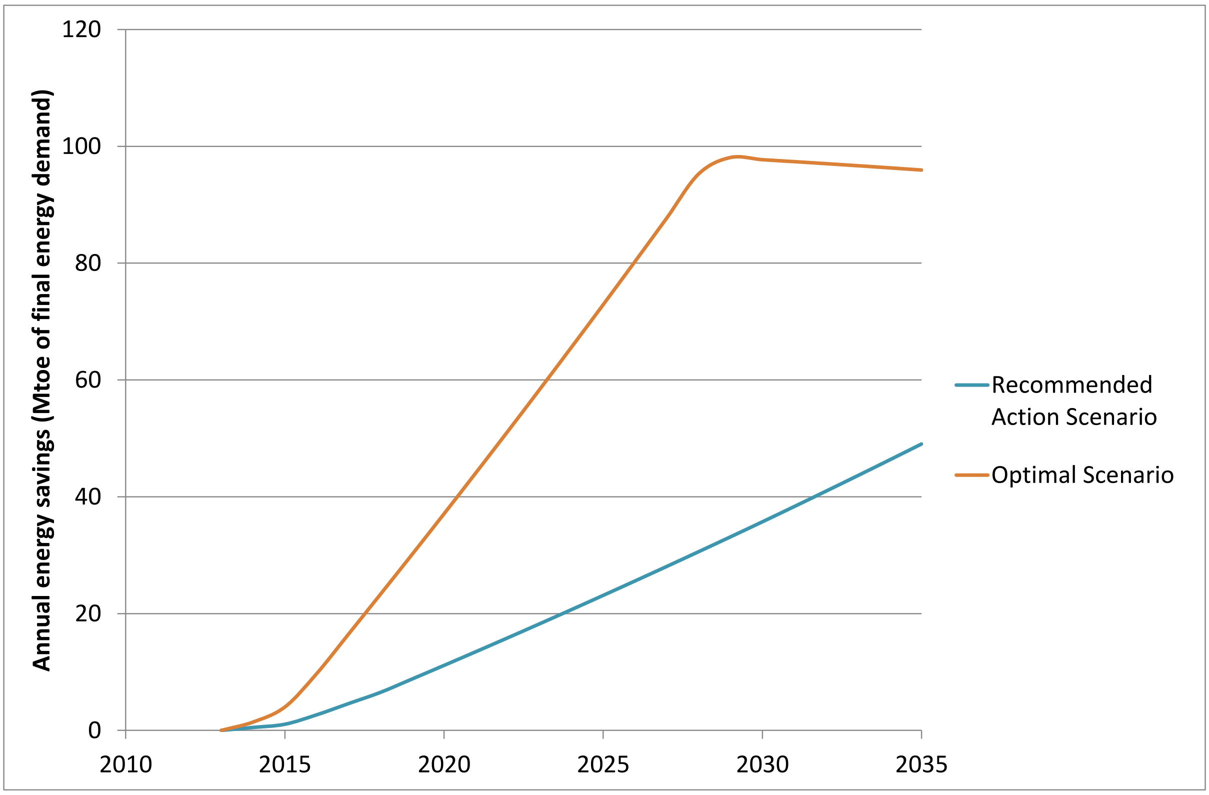

Figure 1. Building energy savings under the Recommended Action Scenario (RAS) and Optimal Scenario (OS) for European residential and service sector buildings compared with the Reference Scenario

The Optimal Scenario leads to some 1 357 Mtoe of cumulative energy savings from 2015 to 2035 compared to the Reference Scenario for residential buildings, while the Recommended Action Scenario leads to some 498 Mtoe of cumulative energy savings over the same period. For the Optimal Scenario this equates to cumulative CO_2 savings of 3.3 gigatonnes, with annual savings of 94 million tonnes of CO_2 in 2020 and 222 million tonnes in 2035[1]. For the Recommended Action Scenario the cumulative CO_2 savings are 1.3 gigatonnes with annual savings rising to 123 million tonnes of CO_2 in 2035.

Over the Recommended Action Scenario period (2013−2035), some €95 billion of extra investments in BAT/HEMS and related services are needed to deliver these savings, at an average of €4.8 billion per year. Large as these incremental investments are, they almost six times less than the value of the resulting savings in energy bills, which total €562 billion over the period, at an average of €28.1 billion per year (Figure 2).

[1] Assuming the same electricity sector fuel-mix and emissions factors as reported in the New Policies Scenario of the IEA's *World Energy Outlook 2012* [4].

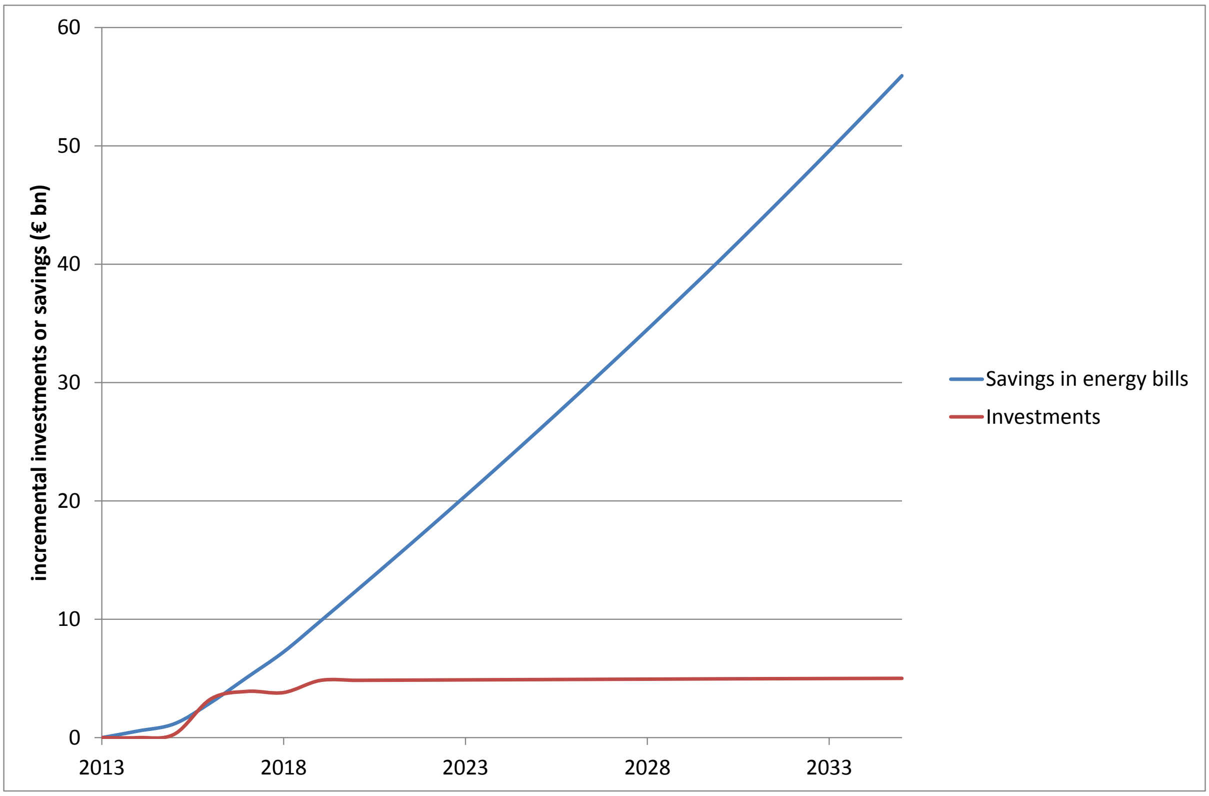

Figure 2. Investments and energy bill savings achievable with building automated controls and technology in European residential and service sector buildings under the Recommended Action Scenario

It is interesting to compare these figures to the cost of roll out of smart meter systems. These are set to cost approximately €95bn to roll out across European homes and are thought likely to produce savings worth about €147bn. Thus a mass EU wide programme to promote savings via BAT/HEMS would cost about the same as the EU's smart meter roll out but produce energy savings which are almost four times greater. Of course the two options are in no way mutually exclusive and should be designed to be complementary; however, it is surprising that the smart meters are much more advanced in the policy attention they receive and their roll out given the relative strengths of the value propositions.

Barriers to energy efficiency

Given this strong value proposition it might be considered surprising that BAT/HEMS are confronting barriers that prevent their more rapid adoption, but in reality they are very similar to other energy saving opportunities in the building stock in this regard. In the case of landlord-tenant arrangements split incentives separate the economic incentive for energy savings from those that procure services but there is an even more important barrier due to the split incentive between the current building owner occupier and the next. In this most common case the present owner occupier will only consider investing in an energy saving technology if they will still be the occupier at the time payback occurs. Given the uncertainty in many people's professional and personal circumstances this is often unknowable in advance. Probably the biggest barrier though is the pervasive lack of awareness of the technical savings opportunity and basic value proposition such that few people even consider such an investment as they're unaware the opportunity exists. Additional barriers relate to (i) access to qualified personnel to design, install and commission automated technology and controls, and (ii) the fact that poor implementation often goes undetected, (iii) lack of common standards enabling BAT/HEMS suppliers to develop more universal products, (iv) slow response from HVAC equipment manufacturers to incorporate advances into their packaged controls and communications and a propensity to use proprietary rather than open source communication protocols, (v) a poor standard of client briefing and technical specification, resulting in lowest-cost solutions regardless of the effect and leading to selection on the basis of lowest capital cost rather than highest value in operation, (vi) the economic situation depressing demand, although perversely the economic situation would result in greater uptake of BAT/HEMS if clients were aware of the cost-benefits that can be achieved from appropriately specified and operated systems, (vii) the magnitude of upfront investment costs for what may seem to be an uncertain value proposition. In addition BAT/HEMS can fail to deliver their full potential because those specifying the system have limited understanding of how it will be operated and have little experience of operating the systems they have specified. In general, there is a need to move to a market where consultants, contractors and suppliers are selected on the basis of their ability to demonstrate that they understand how the BAT/HEMS will be used in operation, rather than just on their design experience.

Recommended actions

Impressive as the savings potentials for BAT/HEMS are, they will not be realised without firm and proactive measures to stimulate both good practice and higher rates of deployment. Very little policy attention has been paid to control systems, which is surprising given that building automated controls and technology have tremendous potential to save energy cost-effectively in Europe’s building stock. All too often, however, the potential is squandered owing to poor design and implementation of the building automated control systems. In addition, uptake of automated energy-saving controls is far below the levels that are economically justified. Thus, fundamentally measures are needed that will:

- increase the reliability of the savings from BAT/HEMS
- increase the uptake of BAT/HEMS.

The recommendations in this section aim to address these needs and to stimulate a debate among energy-efficiency practitioners and policymakers about how best to meet these needs. They are not comprehensive but cover many of the most pressing needs; however, it is recommended that more detailed work be done to refine the analyses considered here (and the related recommendations) prior to any move toward implementation.

Objectives of an ideal policy package

What will an ideal policy package aim to do? On the one hand it needs to drive demand for effective BAT/HEMS installations to overcome market barriers and failures. On the other it needs to stimulate improvements in the practical design, specification and operation of BAT/HEMS to ensure they deliver the savings potential in practice. It is important to appreciate that these two aspects are related, however, as addressing the quality and reliability of savings delivered through BAT/HEMS will also help drive future demand through increasing market confidence in the value proposition of HEMS. There is therefore a feedback between these two objectives. Figure 3 sets out the needs that the various policy measures proposed in the remainder of the paper are intended to address.

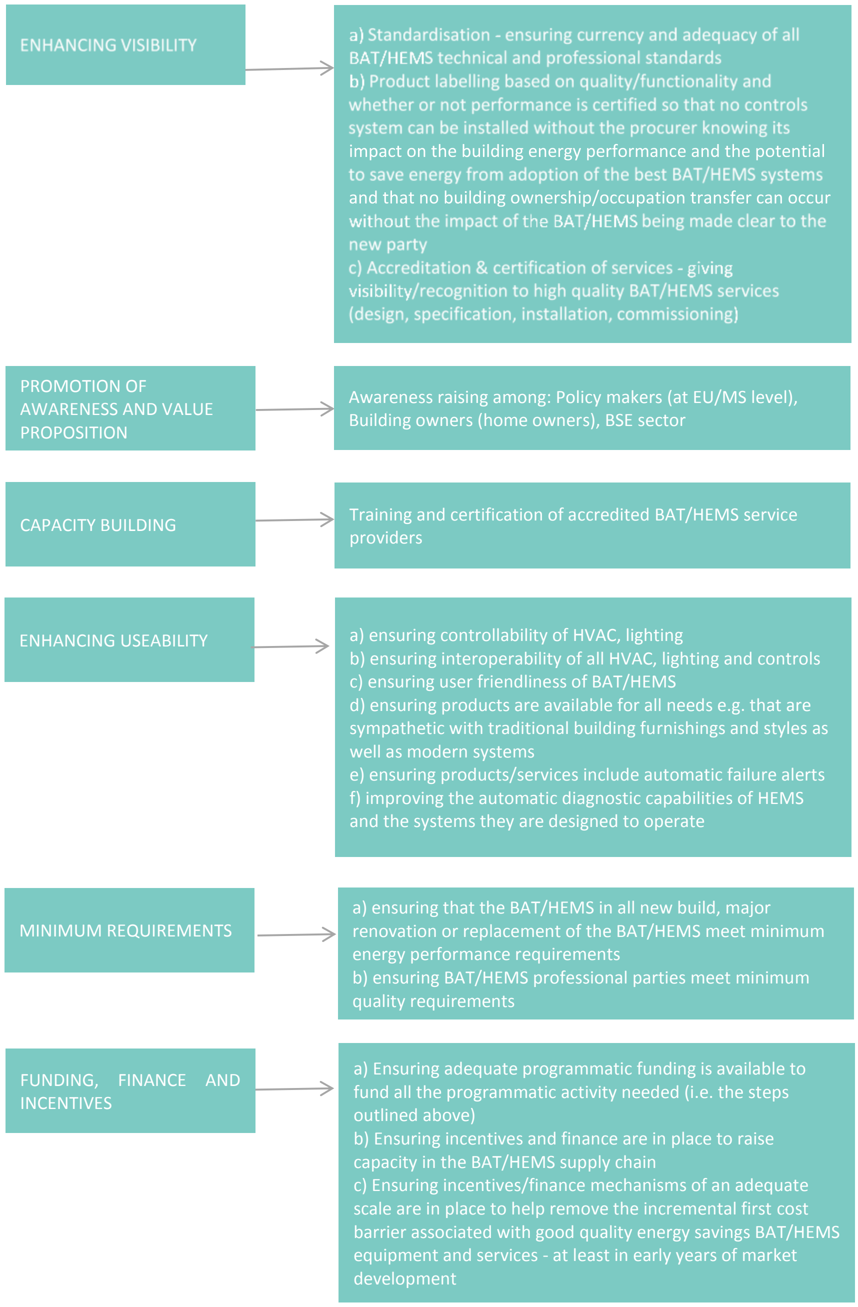

Figure 3. Measures needed to support energy savings from BACS/BAT within an ideal polcy framework

Measures to raise demand

Driving demand can be done through a mixture of mandatory provisions, incentives and awareness raising measures, see Figure 4. Demand can also be raised by improving the reliability of delivered savings.

Mandatory provisions

In principle mandatory provisions can be an effective way of obliging a certain level of service, functionality and performance for automated technology and controls and thus could be used to both drive demand and the quality of service delivered.

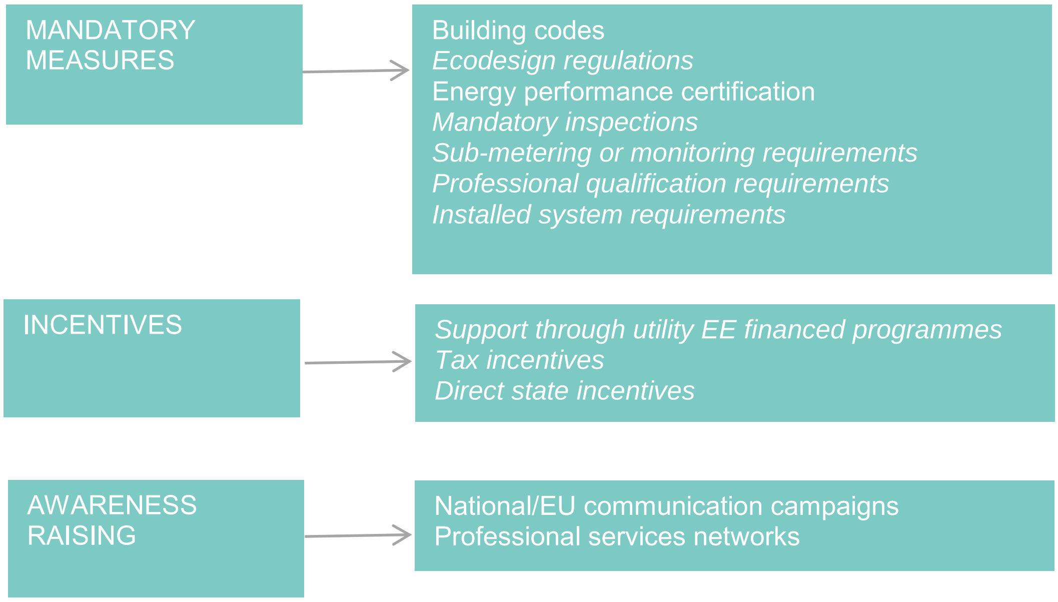

Figure 4. Measures to drive demand

Where they exist mandatory provisions for BAT and energy controls currently comprise installed performance and/or functionality specifications via building codes but could also include:

- Ecodesign requirements
- mandatory inspections
- requirements on building energy performance certification.

In theory they could also involve mandatory professional qualification requirements for BAT/HEMS specifiers and installers. They could further entail mandatory performance and functionality requirements applied to installed systems although such measures have only occasionally be applied for energy using products outside of building codes.

Policymakers will quite rightly only contemplate the adoption of mandatory measures if there is clear evidence of: a market failure that the measure would overcome, a significant net benefit from their adoption and that the measures are practical to implement and enforce. Thus any prospective measure has to satisfy these criteria. It is important to recognise though that mandatory measures can be among the most effective means of addressing split incentive barriers (that pervade the building sector) as well as other barriers such as low awareness and a reluctance to invest in upfront energy savings measures. Given the large scale of cost-effective savings potentials and the myriad barriers to be addressed mandatory measures are clearly appropriate for BAT/HEMS to the extent that they satisfy the criteria set out above.

Building codes

Building codes are designed to overcome first cost and awareness barriers and ensure a minimum level of service adoption; however, it is important to appreciate that they can only practically be applied to new build or major renovations and thus even under the most favourable circumstances will take many years to drive demand in the whole building stock. New build rates in the EU are typically around 0.5% of the building stock per year while major renovation probably applies to about 3% of the residential building stock per annum. Thus while codes are important drivers of demand even under an ideal implementation scenario they will take about 35 years to affect the BAT/controls installations in the majority of the residential sector building stock at best. Given real world implementation deficiencies it would probably be considerably longer in practice.

Furthermore, while all EU Member States have minimum energy performance specifications for whole building energy performance for new build and major renovations it is rare to have specific provisions for building automated technology and controls. This is a lost opportunity because it assumes an unrealistic level of project management and integration in building projects. A more robust policy framework would recognise that there are many actors involved in the design and delivery of buildings and building services, and that each has a distinct role to play in affecting the delivered energy performance. Given the complexity of this arrangement it is better if each type of actor has clearly delineated requirements when these are important to the overall building energy performance. This is especially true for key building energy services such as: HVAC, lighting, and controls (BAT/HEMS). Good practice therefore involves the specification of both overall building energy performance requirements and the specification of separate minimum requirements for the key sub elements; however, this approach is only currently applied among some EU Member States.

The revised EPBD requires MS to determine their codes based on a cost-optimal approach which is supposed to take all energy savings options into account and to set requirements in line with the set of options that produce the least life cycle cost solutions. Inspection of a sample of the cost optimal assessments submitted by MS shows that in the case of building controls this assessment is being done in a very superficial manner at best. It is clear that the cost optimality assessment process within the EPBD is not currently being applied properly by MS for controls and as a result cost-effective energy savings options using BAT/HEMS are either not being considered at all when assessing the cost-optimality of energy performance codes or are being aggregated with other options in such a way that the true benefits are not properly accounted for. This results in both, a reduced appreciation of how much BAT/HEMS can contribute to energy savings objectives and in sub-optimal building codes. Both issues need to be addressed in greater depth in future assessments

Ecodesign regulations

Ecodesign requirements could apply to the BAT/HEMS products themselves were they to be developed. The nature of such requirements is an open question and would need to be investigated via a preparatory study and consultation process but they could include mandatory functionality, interoperability, operability, usability and performance specifications and thereby help to remove inadequate control technologies from the market. They could also include performance classification and disclosure requirements that are either applied through energy labelling (via the labelling Directive) or via information requirements implemented in the Ecodesign Directive. Such classification and disclosure requirements would help to address the low visibility and awareness barriers that currently lead to an under appreciation of the potential for savings from BAT/HEMS. There has been discussion about including BACS in the future Ecodesign working plan for 2015-17 [3] and it is to be hoped that they will be a clear priority. The inclusion of BAT/BACS within this Directive is more important than it may appear at first consideration because it is the best instrument to ensure that all necessary product performance specifications are measured and reported in a standardised manner, which is a necessary precursor to systems integrators being able to confidently specify products to achieve a given energy performance outcome.

Building energy performance certificates (EPC)

EPCs are already a mandatory requirement under the EPBD and each EU Member State has now implemented such measures. The key issue for EPCs with respect to controls is to ensure that the value of good quality BAT/HEMS is recognised and valued within the whole building energy performance rating system and that higher performance BAT/HEMS options are also proposed in the recommended actions within EPCs. In theory this is automatically the case when operational ratings i.e. those based on metered energy consumption, are used - as is the case in many EU countries. However, even here there is no direct attribution of the observed performance level to the BAT/HEMS characteristics and use, so in cases where there is an improvement in the EPC rated score due to the quality of the BAT/HEMS it is unlikely to lead to an appreciation of the contribution to the rating made by the BAT/HEMS. In the case of EPCs which used asset ratings it is important that the role of BAT/HEMS as a function of their capability and quality be adequately recognised within the rating. At present this is rarely the case albeit that the development of the EN 15232 standard [4] now makes it possible to classify and quantify the expected impact of BAT/HEMS on the overall building energy performance. In theory this should allow the gap between asset and operational based EPC ratings to become narrower although in practice there are many aspects of building energy use that are sensitive to occupancy and use factors that are independent of the BAT/HEMS systems used.

Mandatory inspections

Mandatory inspections of heating and AC equipment above 12kW are already a requirement within the EPBD so in principal the same type of requirement could be applied to ensure conformity of building automated controls. Nonetheless, this has been one of the more contentious provisions in the EPBD and it would be advisable to consider means by which the value-added of inspections could be maximised and the burden minimised before imposing new requirements. For BAT/BAC systems this could be done through a triage according to building energy use such that buildings with poor energy ratings and high energy use, as determined by the existing mandatory energy performance certificates could be subject to mandatory BAT/HEMS inspections to see that the level of control capability is sufficient and is properly implemented. Indeed, such a provision is likely to produce much greater savings if competently implemented than mandatory heating and AC systems inspections.

The EPBD was amended when it was recast in 2010 to permit MS to implement alternative measures to mandatory inspections providing that they produce equivalent energy savings as would have been expected from the inspections. The promotion of savings through BAT/HEMS could and should be supported as a principal means of complying with this provision.

Professional qualification requirements

Mandatory qualification requirements could be imposed for the providers of building energy services and controls. Indeed this already happens with respect to safety for gas and electrical equipment and the same principle could be extended to energy performance qualifications. Such requirements would help to raise the quality of service provision but they need to be managed carefully to ensure they stimulate improvements in professional design, specification, installation and operation of BAT/HEMS without creating a strong disincentive to operate within the market i.e. without creating a self-defeating barrier to entry in the BAT/HEMS services market. Often such requirements can be considered when a sufficiently strong professional base has been developed and can be staged in such a way as to progressively raise the bar so that the volume of service provision remains high while the quality is increased. In order to both minimise this risk and to create effective capacity more rapidly they can also be supported by incentives, such as the provision of free or heavily subsidised training and certification schemes. Professional qualifications can also be established for different parts of the supply chain and service sector e.g. in the residential sector training and certification could be developed for:

- BAT/HEMS service providers including designers, specifiers and installers
- BAT/HEMS inspectors and auditors.

Installed system requirements

Despite the inclusion of the “extended product” notion within the MEErP assessment methodology Ecodesign specifications usually apply to components and not to the installed system as a whole, while building codes will only address the quality and performance of BAT/HEMS in the event of new-build or major renovations. This leaves a large gap when new or replacement HVAC systems or their controls are installed that is not easily addressed with the currently implemented measures. This raises the scope, therefore, for a new type of policy instrument aimed at setting requirements for the energy performance of installed systems. It could be designed to apply to a host of systems types including lighting, HVAC, cables, motor systems etc. and if implemented at EU level would most likely would need to be structured with a subsidiarity principle embedded, i.e. more like the EPBD or EED than the Ecodesign Directive in that it could impose obligations on EU Member States to develop and enact installed system requirements according to a common set of principles rather than centrally specifying precisely what such specifications should be. This would reflect that the single market is only lightly involved in the market for installed systems as most service provision is at the local rather than transnational level. Such a Directive would clearly require considerable development work to establish the nature of such an EU driven process, however, the scale of potential savings are such that this effort would be justified and could help complete the EU’s portfolio of energy efficiency legislation. Even in the absence of such EU measures individual Member States could develop their own requirements should it not prove to be possible to develop a common EU framework. In principle Article 8 of the EPBD, which requires MS to specify requirements for technical building systems, including heating and lighting systems, could be implemented to fulfil this function.

Incentives

Incentives help overcome the first cost barrier, the awareness barrier and the split incentives barrier (both landlord tenant but also the split in incentives between the current owner/occupier and the next). They are thus a key instrument to help establish delivery at scale when mandatory measures are insufficient or only partially address the need. If applied appropriately they will be tied to clear quality of service requirements to favour and differentiate quality service providers over those that do not meet service quality requirements. This will create an incentive for BAT/HEMS service providers to demonstrate that they meet quality requirements and thereby raise the quality of service offered, which in turn will improve customer experience and hence drive repeat business and future demand. In this way they can help to increase the capacity to deliver good quality BAT/ HEMS and related services. Incentives can also be structured to:

a) Prime the market and raise capacity ahead of the adoption of mandatory measures – such as stricter building code specifications

b) Be staged to be relatively generous in the early stages of a market stimulus effort but subsequently phased down as the market volume builds, mandatory measures are locked in and confidence in the value proposition of BAT/ HEMS increases.

These two aspects echo previous market transformation initiatives that were successfully applied, for example, for gas condensing boiler technology in the UK and Netherlands wherein generous incentives introduced at the early market stage helped to both drive demand and build delivery and installation capacity, prior to being ramped down and locked-in via mandatory regulations once the capacity of the market to deliver a good quality product in all applications and at scale had been established.

In theory incentives can be applied to:

- bring down the cost of good quality energy saving BAT/ HEMS and drive demand
- build capacity in the supply chain
- encourage HVAC and lighting systems to be fully interoperable and controllable using HEMS
- support diversification of residential product offers so that the range of controls on offer (especially for heat emitters) are better adapted to the aesthetic sensibilities that exist in the European building stock (particularly for prevalent older building types and periods) and hence will have greater consumer acceptance.

Financing for incentives needs to be of a sufficient level and quantity over a sustained period if energy saving policy objectives are to be realised. In most economies public sector finance is likely to be too modest and unreliable to meet the scale required therefore it is likely to be more viable if the finance is derived from the value of avoided future energy bills. This can be implemented through mechanisms such as utility energy efficiency obligations which recover the cost of energy efficiency measures via modest increases in energy tariffs in such a way that net bills decline i.e. so energy bill payers are both the financer and net beneficiary on aggregate[2]. In principle the notion of a feed-in tariff applied to energy savings measures, such as BAT/ HEMS, could also serve this function.

Unfortunately a review of the existing energy efficiency incentive schemes applied to buildings in EU MS shows that very few appear to offer specific encouragement to BAT/ HEMS and thus it appears that in practice such incentive schemes are not yet being widely used to promote savings from this route. Much more work is clearly needed to determine what kind of incentives could be applied productively to what kind of BAT/ HEMS technologies under which conditions, however, given the vast scale of cost-effective savings potentials it clearly needs to be made a priority.

Awareness raising measures

Low awareness of the value proposition of BAT/ HEMS is a critical issue and is even more prevalent in the residential sector than the service sector, but very widespread in each. Therefore, efforts to

[2] This is the same model used to fund the roll out of smart meters

raise awareness of the value proposition are vital to drive demand. This is crucial to help address the visibility and priority barriers and thereby stimulate a more natural market for quality BAT/ HEMS and related services. First it is essential to spread the message about the value proposition of effective BAT/ HEMS so that organisations and individuals become more cognisant of how much they can save cost effectively from applying BAT/ HEMS more effectively. The development of a European and national communication strategy that explores the various media and networks that could be accessed to effectively convey the message would greatly support this objective. Such strategies would be likely to have much greater impact if they're linked to incentives supporting a mass roll out.

Improving the quality of delivered savings

Equally important to measures aimed at driving up demand are those aimed at improving the reliability of savings from BAT/ HEMS. Indeed the two are strongly related as the autonomous market demand for BAT/ HEMS will rise if the quality (reliability) of assured savings increases. Part of the process to raise the quality of delivered savings through BAT/ HEMS involves measures to raise the technical capacity of those involved in the supply and delivery of the savings i.e. of: the BAT/ HEMS systems specifiers and of the HVAC and lighting systems specifiers, installers and commissioners. In the residential sector continuous commissioning is not likely to be viable and regular energy audits can be difficult to implement effectively thus it is important to develop automatic diagnostic systems that can detect failures in control or operation and alert people to them. In the European building stock space heating is the largest end-use and its control should be the main focus of these efforts.

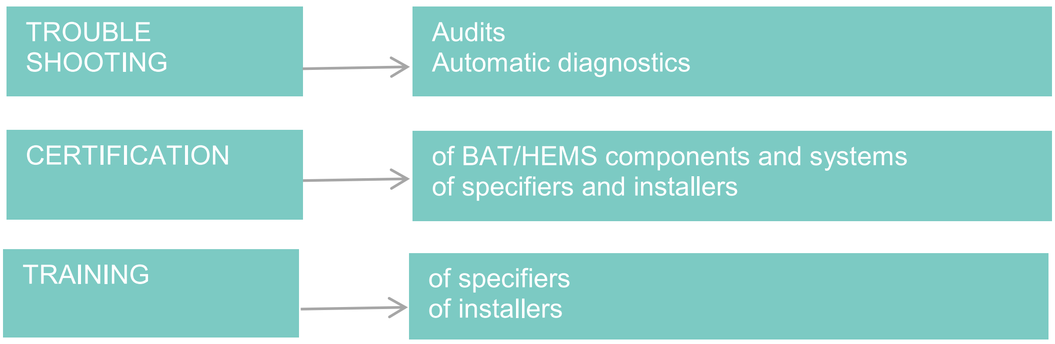

Figure 5. Measures to improve quality of residential BAT/HEMS energy savings

Regular audits

Regular audits (which can sometimes be grouped with regular commissioning or re-commissioning) will help to identify failures in the BAT/HEMS set-up and operation. Audits could be done purely to address such issues i.e. be dedicated BAT/HEMS audits or could be done to identify broader sets of energy savings opportunities including BAT/HEMS. The eu.bac BACS certification scheme promotes regular audits as a less costly version of continuous commissioning; however, these are focused on service sector rather than residential sector buildings.

Improving automatic diagnostics

Diagnostic and auditing systems are essential to ensure proper operation of complex control systems. Ideally these need to go beyond simple hardware and software solutions (albeit these are the core of the solution) to become fully embedded with corporate human organisational structures into a quality assurance process.

There is also a role for R&D designers to improve the automatic diagnostic capabilities of BAT/HEMS and the systems they are designed to operate. Methods to automatically highlight deficiencies in building services and associated controls performance are needed as it is unviable for experts to analyse system performance for all buildings on an ongoing basis from a practical and financial viewpoint. Excessive energy consumption can be identified with relatively simple rules, and there is considerable potential for expert and other rule-based automated diagnostic systems to identify wastage. Manufacturers and others have undertaken some development in this area, but little has yet been commercialised. In addition to expert systems, techniques such as data mining also have considerable potential. These can identify patterns in the vast amounts of data available from HEMS and can identify when systems are not working as expected. They can assist in the ongoing analysis of systems to improve energy performance and, as with expert systems, identify when systems are performing poorly and the likely causes. It is therefore recommended that advanced data-analysis techniques and routes to market be developed.

Quality certification

Significant capacity constraints affect the proficient delivery of the energy savings potential of building automated controls involving at least the following:

- inadequate specification and installation of building energy controls and automation systems
- improper commissioning of BAT/HEMS
- insufficient knowledge of BAT/HEMS, options and practices among building code and energy performance certification requirement designers.

Consequently, it is recommended that structured efforts be made to develop a supply of high-quality service providers through the establishment of dedicated training, certification and accreditation efforts.

Certification of BACS and of specifiers and installers

It is extremely important to ensure the quality of the BAT/HEMS (components and systems), their specification and installation; and as a result it is highly desirable to promote and develop quality certification of all these aspects of the supply chain. The European Building Automation and Controls Association, eu.bac, has recently taken the lead in this and has developed a voluntary certification programme [5]. This is a commendable initiative but is relatively modest in the scale of its implementation as it is being rolled out among some eu.bac member companies in a few selected MS. It is therefore essential that public authorities engage with this initiative to increase its volume of application with the aim of ensuring all professional practitioners are suitably qualified in the future.

Training of building service engineers

The training of building service engineers involved in the design, specification and installation/commissioning of HVAC/lighting systems and BAT/HEMS also needs to be strengthened to take on board the controllability of the energy using systems, the options and features of BAT/HEMS and how to configure optimised systems. Programmes to deliver such training need to be designed, trialled, refined and then rolled out at scale.

How should the Commission implement the EPBD, EED and Ecodesign with respect to BAT/HEMS?

Most of the potential power of the EPBD to produce cost-effective savings through BAT/HEMS is currently untapped. To help address this it would be helpful were the Commission to:

- Ensure that the Article 8 provisions regarding setting energy performance requirements for technical building systems are properly elaborated for BAT/HEMS and appropriately implemented
- Ensure BAT/HEMS are included in MS calculations of whole building (or renovation) energy performance in a sufficient level of detail to capture the diversity of outcomes and to reward good practice so that their contribution can be properly accounted for in delivering prescribed whole building or renovation performance levels
- Encourage MS to take BAT/HEMS properly into account in the determination of rankings for energy performance certificates and to include BAT/HEMS options among the set of options recommended to improve performance
- Encourage MS to complement whole building (or renovation) energy performance requirements with minimum requirements for BAT/HEMS to ensure that building services are deploying cost-effective control strategies
- Ensure that the cost optimal methodological assessment used to define or justify the codes at MS level includes a proper assessment of BAT/HEMS differentiated by their various levels of

functionality and that these are not aggregated with other options that might be less cost effective to implement
- Develop guidelines regarding the design of programmatic actions to stimulate savings through BAT/HEMS as an alternative means of complying with Article 14 requirements on the inspection of heating systems
- Develop guidelines on how best to treat BAT/HEMS within EPCs
- Encourage MS to consider partially satisfying Article 10(2) requirements regarding financial support measures with measures that target effective BAT/HEMS deployment
- Encourage MS to amend their application of EPCs to analyse the difference between asset and operational ratings and using this to provide direct guidance on the need to improve the control strategy (as discussed in the EPC section above). If necessary, trial this concept and support the development of analytical tools to support this process.

In general it can be said that while provisions requiring the use of adequate controls in new buildings and renovations are necessary to stimulate uptake of energy-saving controls, there needs to be much greater reflection regarding how they should be framed and specified to ensure that they are clear, usable and encourage good practice. It is therefore recommended that an expert task force be established to prepare guidelines on these specifications and to review/critique existing specifications. To ensure that the recommendations reflect real application, the task force should include review from practitioners who would be expected to use the requirements and not just from experts in the control industry or researchers. Once clarity on the optimal regulatory specifications has been established, EU Member States should move to implement them fully in their building codes and to monitor implementation experience to ensure desired results are being achieved, making informed adjustments if not. The European Commission could facilitate coordination of this process.

The EED has a great many articles that could be applied to strongly promote energy savings through BAT/HEMS but at present there is very little evidence in MS submissions via the NEEAPS or other documents that they are applying these provisions to the realisation of savings through BAT/HEMS. In particular BAT/HEMS could be promoted through:

- Funding and incentives derived via Article 7 on Energy Efficiency Obligations
- The development of fully qualified professionals via Article 16 – Availability of qualification, accreditation and certification schemes
- The mobilisation of renovations for the existing building stock under Article 4 – Building Renovations

In the case of Ecodesign explicit implementing measures which could be developed to apply to BAT/HEMS products directly include:

- Requirements on interoperability (i.e. to ensure or encourage products to use open communication and control standards so that they can work with the maximum proportion of HVAC and other energy services equipment)
- Requirements on functionality (i.e. to ensure or encourage products to have sufficient functionality to enable significant savings to occur)
- Requirements on usability (i.e. to ensure or encourage products to be more user friendly, perhaps through adoption of common user interface templates in line with industry best practice, but also (depending on the product type) to provide alerts when extreme energy losses occur (e.g. when the same zone is being heated and cooled))
- Development of a common performance classification scheme leading to requirements on the disclosure of the classification perhaps via labelling or a rating disclosure process (either as components or within a larger system classification scheme)
- Requirements on the sensitivity and permitted tolerances of BAT/HEMS
- As a stimuli to repeat commissioning via a requirement for an inbuilt alarm when a set period has passed since the last system commissioning

A summary of the current status and potential for existing EU policy instruments to be applied to the support of BAT/HEMS is indicated in Table 1.

Table 1. Summary of current EU policy instruments as they are and could be applied to BAT/HEMS

Directive	Measure								
EPBD	**Building Energy Performance Codes**					**EPC**		**Incentives (Article 10(2))**	**Article 14. In place of HVAC inspection**
Scope	New build	Existing buildings	Residential	Non-residential	Cost optimal assessment (Article 5)	Residential	Non-residential	All buildings	All HVAC or equivalent measures
Status	Mixed, BACS mostly not treated explicitly	Mixed, BACS mostly not treated explicitly	Mixed, BACS mostly not treated explicitly	Mixed, BACS mostly not treated explicitly	BACS are mostly not assessed explicitly, if at all	No evidence any MS has considered applying this article to BAT/BACS explicitly	No evidence any MS has considered applying this article to BAT/HEMS explicitly	No evidence any MS has considered applying this article to BAT/HEMS explicitly	No evidence any MS has considered applying this article to BAT/HEMS
Notes	Should have specific BAT/HEMS requirements in all MS codes	Should have specific BAT/HEMS requirements in all MS codes	Should have specific BAT/HEMS requirements in all MS codes	Should have specific BAT/BACS requirements in all MS codes	Should treat BAT/HEMS explicitly and in sufficient detail to see cost-benefits	Should treat BAT/HEMS explicitly and be included in recommendations	Should treat BAT/BACS explicitly and be included in recommendations	Should treat BAT/HEMS explicitly	BAT/HEMS promotion are an ideal alternative means of meeting this Article
ECODESIGN/LABELLING	**MEPS**	**Classification/Labelling**	**Other requirements**						
Status	BACS under consideration for possible inclusion in work plan	BACS under consideration for possible inclusion in work plan	BACS under consideration for possible inclusion in work plan						
Notes	BAT/HEMS should be included	BAT/HEMS should be included	BAT/HEMS should be included						

Table 1. Summary of current EU policy instruments as they are and could be applied to BAT/HEMS continued

Directive	Measure							
EED	**Article 7. Utility energy efficiency obligations**	**Article 20. Energy Efficiency National Funds**	**Article 4 – Building Renovations**	**Article 8 – Energy Audits**	**Article 14 – Promotion of efficiency in heating and cooling**	**Article 16 – Availability of qualification, accreditation and certification schemes**	**Article 19 MS shall evaluate and remove barriers to EE**	
Status	Mixed/weak implementation. Not all MS have them. Many EEOs (almost all) are not yet designed to apply to BAT/HEMS	Mixed/weak implementation. Not all MS have them. Many funds (most) are additional and are not yet designed to apply to BAT/HEMS	Do they apply to BACS? Not all MS have them	No evidence any MS has considered applying this article to BAT/HEMS	No evidence any MS has considered applying this article to BAT/HEMS	No evidence any MS has considered applying this article to BAT/HEMS	No evidence any MS has considered applying this article to BAT/HEMS	
Notes	Measures targeting BACS could meet about half of the MS savings targets by 2020. EEOs could fund BACS including BAT/HEMS programmatic measures	These could be designed to support BAT/HEMS programmatic measures	Should include BAT/HEMS provisions	Should include BAT/HEMS provisions	Should include BAT/HEMS provisions	BAT/HEMS are in serious need of these and thus should be one of the first foci for this article	Each MS should assess barriers to BAT/HEMS savings and devise remedial actions accordingly	

Conclusions and the way ahead

Overall it is clear that the existing EU policy framework contains plenty of levers and opportunities that could be applied to the promotion of BAT/HEMS and that could treat almost all the ideal policy package needs. In practice though very little of this has actually been applied to the realisation of cost effective savings from BAT/HEMS. This is mostly because these policy levers are aimed at addressing a number of horizontal energy savings opportunities of which BAT/HEMS is but one (albeit one with a very large unexploited savings potential). In principle the approach taken with the existing measures might appear to make sense i.e. a policymaker might ask why should one be prescriptive about the means of reaching a savings objective if any number of measures are eligible and could meet the objective? However, the reality is that the vagueness about how to address the savings coupled with the lack of appreciation of the scale of opportunity posed by BAT/HEMS means that the topic simply hasn't received the attention it deserves, neither in Community-wide policy packages nor in MS implementation plans. This lack of focus is a missed opportunity because almost regardless of whether other energy savings opportunities are realised or not the cost effective potential from BAT/HEMS alone will remain of the order of 7% of EU final energy consumption and has a direct bearing on strategically important issues such as the dependency of the Community on imported gas. There are at least two potential remedies to this. One is to take all the existing EU policy levers (building codes; EPCs; HVAC inspections or equivalent savings measures; EE funds and incentives; EEOs or equivalent savings measures; availability of qualification, accreditation and certification schemes; energy audits; Ecodesign and labelling requirements) and ensure that they are applied directly and explicitly to deliver a coherent savings plan for BAT/HEMS. Alternatively a dedicated piece of legislation could be developed that targets BAT/HEMS savings explicitly. The best candidate for this latter option would be a dedicated piece of legislation to develop requirements on the energy efficiency of installed systems. This could focus on more than just BAT/HEMS but would be likely to produce additional benefits in terms of clarity of focus, implementation and outcome than might be expected from a proactive pursuit of the first option. However, this would also require political will with an agreed vision among MS and the Commission in order to bring this about, so practically it makes sense to pursue opportunities in both directions simultaneously in order to ensure meaningful action occurs via one route or another.

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Using PAMS to estimate savings potential from increased energy efficiency – a case study

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Abstract

What would you do if you had to estimate the energy savings potential from adopting energy efficiency policies for three household products in each of 33 countries, and had only two months to do it? The authors faced exactly this challenge in 2014.

For the task, the authors chose the Policy Analysis Modeling System (PAMS) [1], a free and publicly available impact model implemented in Microsoft Excel. PAMS was developed more than ten years ago by Lawrence Berkeley National Laboratory (LBNL) in collaboration with CLASP to provide first-order policy impacts projections with a minimum of preparatory research on the part of local policymakers.

PAMS comes pre-programmed with a host of inputs, including cost-efficiency curves and electricity prices, so users can identify the most cost-effective efficiency level to target with their policies. PAMS provides these inputs for three products—air conditioners, refrigerators, and clothes washers—for more than 100 countries. In the absence of reliable market data for a given country, PAMS can forecast the size of the market for a given product in that country based on climate and macroeconomic indicators such as household income.

Using PAMS, the authors estimated that the 33 countries of Latin America and the Caribbean (LAC region) could save a total of 137 TWh of electricity in 2030 if they adopted advanced energy efficiency standards for refrigerators, air conditioners, and ceiling fans by 2020. That is approximately 11% of current annual electricity use in the region.

This paper will describe how the authors customized and updated PAMS to suit the task at hand. Learn how PAMS was modified to analyze fans instead of clothes washers and to produce results for several small countries not included in the public version. Learn how the cost-efficiency curves and macroeconomic indicators were updated. The paper will also discuss how the authors used contemporary market data from several sources to improve the model's forecasts.

The paper will be of great value to the energy efficiency practitioner who is looking for an easy-to use yet sophisticated tool with which to estimate energy efficiency potential from product policies.

Introduction

The analysis described in this paper was developed in the framework of the Global Efficient Appliances and Equipment Partnership Programme, a public-private initiative led by the United Nations Environment Programme (UNEP), CLASP, the United Nations Development Programme (UNDP), the International Copper Association (ICA), and the Natural Resources Defense Council (NRDC) to accelerate the transition to more efficient appliances and equipment to reduce global energy demand, mitigate climate change, and improve access to energy.

This assessment aimed to highlight the opportunities in terms of energy and economic savings from a transition to energy efficient products in Latin American and the Caribbean (LAC) countries. Energy demand for cooling applications (such as refrigeration and air conditioning) is on the rise and expected to increase up to 61% between 2010 and 2030 in the absence of energy efficiency policies.[2] The economic and energy savings potential from adopting more efficient refrigerators, air conditioners and fans were analyzed in the LAC region: if the 33 countries adopt advanced energy efficiency standards for the three product categories, they could save 137 TWh of electricity in 2030, equivalent to 11% of current energy demand in the region.

Methodology

The team was tasked with analyzing economic and energy savings potential from a transition to more efficient appliances with limited time and resources for data collection. The analysis required the establishment of a base case for each appliance under the scope (or a base line considering an average product and its related energy consumption); definition of a policy case (or energy efficient option); relevant country data to characterize the electric sector (electricity rates, CO_2 emissions factors); and product market data to estimate present and future sales and stock. Considering that this process was taking place for three products in 33 economies, the team considered several available tools that would facilitate calculations (i.e., number of model runs) and would enable filling some of the data gaps through modeling.

Three appliance energy efficiency impact models were short listed, as they can be used to estimate the energy and greenhouse gas (GHG) impacts of improvements in market average product efficiency from the current year and up to 2030: the Bottom-Up Energy Analysis System (BUENAS), the Product Policy Analysis Tool (PPAT), and the Policy Analysis Modeling System (PAMS or PAMS-MEPS). The main characteristics of each model are summarized in the table below:

Table 1. Primary uses for and key characteristics of three appliance energy efficiency policy impact models

	BUENAS	PPAT	PAMS-MEPS
Primary Use	Sum energy savings potential across various products and 13 major economies	Compare and contrast energy savings potential across various products in a single economy	Find the most cost-effective efficiency level for a single product in a single economy
Key Points of Differentiation	Already contains market and efficiency data for various products and countries	User friendly Built-in data visualization tools Can estimate peak demand impacts	Can conduct the economic analyses needed to support policy development

In addition to the key points of differentiation above, there are major differences among the three models in the types of inputs, outputs, product and country coverage, and additional features. These are listed in the table below to facilitate comparison.

Table 2. Side-by-side comparison of three impact models

Model characteristics		BUENAS	PPAT	PAMS-MEPS
Purpose	**Estimate Impacts (Energy and CO_2)**	X	X	X
	Assess Ease of Policy Implementation		X	
	Compare Across Economies	X		
	Design Cost-Effective Policies			X
Scope	**Economies**	13 major economies	India only; extensible	150 countries
	Sectors	R, C, I[1]	R, C, I	R
	Products	More than 30	More than 30	Refrigerators, Room AC, clothes washers; extensible

[1] R: residential, C: Commercial, I: Industrial.

Model characteristics		BUENAS	PPAT	PAMS-MEPS
Fuels		Electricity, Natural Gas, Fuel Oil	Electricity, Fuel Oil, Gasoline, Kerosene	Electricity
Key Scenarios		BAU, Cost-Effective Savings, BAT[2]	BAU, Multiple User-Defined	BAU, MEPS (multiple levels)
Inputs	**Sales or Stock Time Series**	X	X	X
	Sales Growth Rate		X	
	Unit Energy Consumption	X	X	X
	Demand (Coincidence) Factor		X	
	Product Lifetime	X	X	X
	Product Prices			X
	Energy Prices	Optional		X
	Discount Rate	Optional		X
	Other Macroeconomic Variables	X		X
Outputs	**Stock (Each Year)**	X	X	X
	Sales (Each Year)	X	X	X
	Energy Demand (Consumption)	Final Energy[3]	X	Primary Energy[4]
	Electric Peak Power Demand		X	
	CO_2 Emissions	X	X	X
	Economic Impacts (National)			X
	Economic Impacts (Consumer)			X
Time Dimension	**Base Year for Market Data**	2005	2010*	2010*
	Policy Implementation Year	2015	=Base Year	2010*
	Time Horizon	2030	2030*	2030*
	Time Increment	1 year	5 years	1 year
Features	**Open Spreadsheet**			X
	Built-in Visualization Tool		X	X
	Can Assume Non-Zero Price Elasticity of Demand			X
	Can Assume Declining Product Prices (Learning)			X
	Can Assume Efficiency Improvement in BAU Case	X		X
Publicly Available				X

* The user can adjust this parameter as desired.

The PAMS model offered features that were advantageous in this assessment, mainly:

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[2] BAU: business as usual, BAT: best available technology

[3] This quantity is also sometimes called “site” or “delivered” energy.

[4] This quantity is also sometimes called “source” energy.

- Macroeconomic data for economies under analysis are already available. The data already refers to possible sources of information and can be updated as required if more recent data becomes available. This can greatly reduce the time an analyst needs to compile data for multiple economies (i.e., 33 countries in this case).
- Built-in saturation functions to forecast appliance ownership levels for two of the appliances under analysis (refrigerators and air conditioners). These functions are especially helpful in economies where S&L are not yet in place and thus it is unlikely data will be available to characterize market sizes and growth.
- Ability to conduct cost-benefit analysis of potential policies.

There were three key disadvantages:

- PAMS does not have built-in household saturation parameters for fans
- PAMS cannot produce results for a series of products or countries simultaneously, in contrast to BUENAS and the PPAT, where all the inputs for each country and product are entered before running the model. This can increase the time to produce results, as each country-product combination must be run independently.
- Technology options to characterize the base case and policy scenarios are out of date.

A major constraint for the analysis was the lack of available market data for most of the 33 countries; thus the ability of PAMS to generate sales and stock forecasts based only on macroeconomic indicators was considered a major advantage, as was the ability to conduct cost-benefit analysis. The authors, therefore, chose PAMS for the task and made a number of updates and customizations to address the disadvantages of this model, as explained below.

Data collection, sources, and limitations

There are three types of data that need to be collected or defined as a minimum for this type of analysis:

1. *Country data* to define the energy sector and economic indexes of an economy
2. *Product market data* to characterize the market size and expected growth (both in terms of sales and stock)
3. *Energy use data*: includes the definition of the base case (current product energy performance) and the policy case (more efficient option)

The team made an effort to gather the most recent data for the three categories above in order to reduce the number of uncertainties and produce reasonable estimates, as required by the task at hand.

Updating *country data* was feasible due to the large number of available databases that track information such as population, household size, urbanization, and electrification rates. International organizations such as the UN, the World Bank and the IEA provide access to some of these data, with the advantage that reported data (for all economies) uses the same methodology for quantifying and reporting. Other relevant data to characterize the electricity sector in each economy, such as electricity prices and CO_2 emissions factors, were updated with information from country representatives. There might be some differences in these reported values, as methodologies to estimate average electricity prices or the CO_2 emissions factor vary by agency or by country.

Product market data were more difficult to collect as there is no single source or agency tracking sales in a consistent manner in the economies under scope. The team used mainly three sources of information in order to develop an understanding of the market and trends for each economy:

1. UN COMTRADE databases, which provides information on the number of units and monetary value of exports and imports by product and by country
2. Euromonitor International, a market research firm that collects sales data from a number of sources and provides historical and forecast sales figures for many products and countries
3. Manufacturer partners, who provided sales estimates for select countries and products

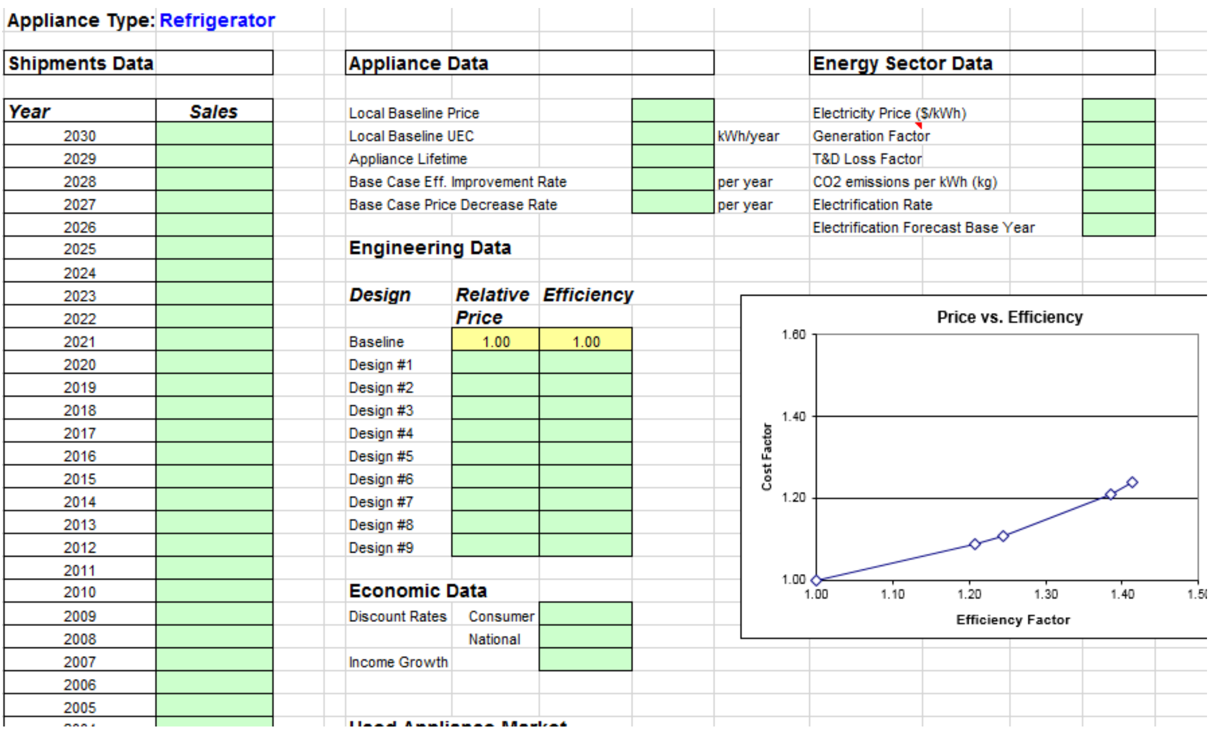
For each product-country combination, the authors triangulated between the available data sources, including the sales and stock forecasts PAMS produced using macroeconomic data. Each source has limitations. The COMTRADE database does not capture products produced domestically. The reliability of Euromonitor data varies from country to country and product to product, based mainly on the availability and reliability of underlying data sources. Data provided by manufacturers might not be representative of the whole market. Nevertheless, in the absence of a more reliable dataset, these data sources were used to put lower and upper bounds on sales and stock estimates obtained from PAMS, and to develop corresponding adjustments if necessary (i.e., if PAMS was significantly under- or over-estimating actual sales).

Energy use data is the most difficult category, as manufacturers are not required to report energy performance unless there is a standard and labeling (S&L) program in place requiring product registration. Since the task aimed to estimate potential energy savings from a policy scenario—a transition to more efficient appliances—a base case was selected that was representative of a market where S&L is already in place. In countries where there is no S&L in place, products are most likely less efficient and thus selecting a more efficient base case would yield lower energy savings. Thus, this was a conservative approach that would provide enough information for a country to decide whether or not an energy efficiency policy is necessary.

The selection of representative base cases and policy scenarios drew on data available from multiple sources. Important sources of such information included the technical support documents (TSD) developed by the US Department of Energy, which explain the technical analyses and results supporting the development of energy conservation standards, and the Preparatory Studies that provide technical evidence needed to draft implementing measures (i.e., minimum energy performance standards) under the Ecodesign Directive of the European Commission. The authors also made use of techno-economic analyses conducted by Lawrence Berkeley National Laboratory (LBNL) in support of the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative. These documents provided extensive technical information on the energy performance and cost of products at various efficiency levels commercially available when those analyses were conducted.

The PAMS workbook includes a tab named “User Inputs,” which allows the user to override many of the preset input values. (See Figure 1.) The authors made liberal use of this capability. As discussed above, the shipment (or sales) time-series “default” values generated within PAMS needed to be adjusted in many cases in light of other available data. The adjusted values, once pasted into the User Inputs sheet, overrode the default values.

Figure 1. User inputs tab in PAMS which can be used to override default values

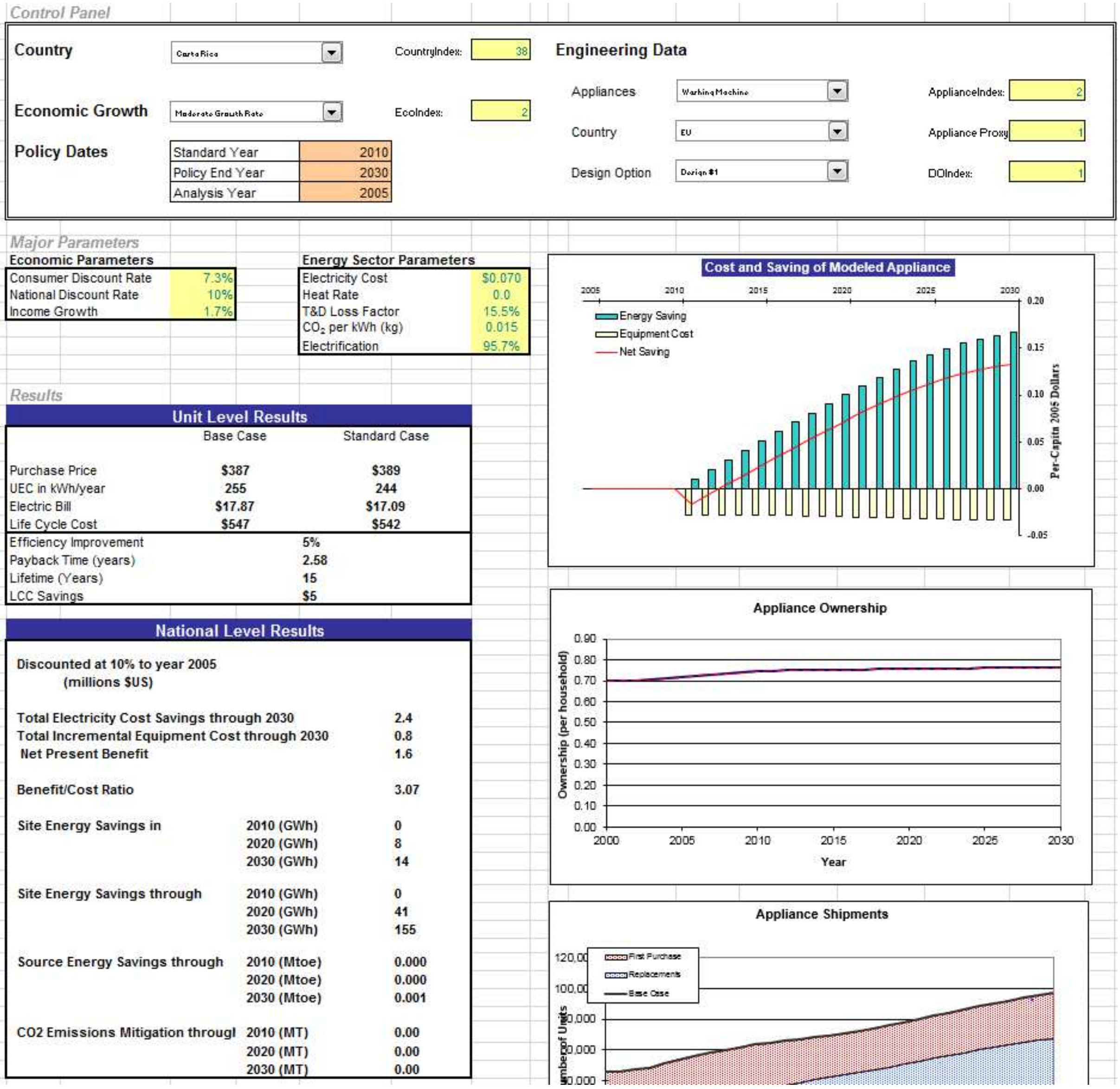


Limitations of the model

This section identifies specific limitations of PAMS and the customizations the authors implemented to overcome these limitations.

As mentioned earlier, PAMS produces results for one product in one country at a time. Figure 2 shows the tab that contains user controls, major input parameters, and summary results. The authors created a place within the workbook where all of the key outputs from a single model run were displayed in a single column. The values in that column could then be copied and pasted easily to another tab holding the results for all 99 model runs (3 products x 33 countries). PAMS does not offer a way to determine the efficiency level that minimizes consumer lifecycle cost. However, Excel's goal seeking function can be used for this purpose.

Figure 2. Summary tab in PAMS containing user controls and showing key results



The public version of PAMS contains formulas and coefficients for estimating household penetration levels for refrigerators, air conditioners, and washing machines, but not ceiling fans. The authors replaced the formula for washing machines in PAMS with the diffusion equation for ceiling fans specified in a study LBNL conducted for the SEAD Initiative [3].

Some of the 33 countries under study, generally the small island nations, are not included in the public version of PAMS. The authors first examined the original sources of country-specific data in PAMS to determine whether those sources contained data for the missing countries. If data were not available from those sources and other suitable sources could not be identified, similar countries were identified and used as proxies. Data for dozens of small countries in other regions of the world are also not included in PAMS.

PAMS contains a single electricity price for each country and offers no easy way to have this price change over time. For the analysis in question, a constant electricity price assumption was satisfactory, though other analysts may find this an important limitation of the model.

PAMS estimates both the site and source energy savings resulting from a transition to more efficient products. It does not, however, estimate peak demand savings. Such estimates were not required for the analysis in question. Crude estimates of demand savings can be obtained from the energy savings estimates assuming an annual average capacity factor. To get a more accurate picture of the relationship between improving the energy efficiency of a given product and the resultant effect on peak demand requires understanding when that product is used relative to periods of peak demand. With these so-called coincidence factors in hand, the analyst could use outputs from PAMS to develop reasonably accurate estimates of peak demand savings.

Recommendations and potential solutions for analysts

Analysts embarking on similar projects are encouraged to explore their options and seek out a tool appropriate to the task. But that is only the first step. Finding the data needed as inputs is usually a much more challenging component of any such analysis. This paper identifies several sources of such data.

Unfortunately, much of the data needed for appliance policy analysis is expensive or highly dispersed and difficult to access. There have been some efforts to collect data in the public domain and present them in a standardized and usable form. Three examples are the ODYSSEE Database [4], the Green Cooling Initiative [5], and the en.lighten initiative [6]. The ODYSSEE Database is, among other things, a source of appliance usage data for Europe. The Green Cooling Initiative publishes country data sheets containing sales and stock estimates for refrigeration and space cooling appliances. The en.lighten initiative offers detailed lighting usage and market data for each of more than 100 countries. Much more could be done to gather in one place and catalog the product market and usage data which are foundational for energy efficiency policy analysis.

A large volume of product market data is now available in the public domain in the form of retailer websites and government certification databases. From these sources, the analyst can develop a reasonably accurate picture of the price, efficiency, and other attributes of products on the market today. The SEAD Initiative, recognizing the value of these resources to policymakers, defined a framework and standards for collecting and mining data retrieved from these sources [7]. Analysts around the world are starting to take advantage of this framework to gain access to timely market data and make better decisions.

More information about the three tools and underlying data described in this paper is available from LBNL, CLASP, and the SEAD Initiative.

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APPLIANCE EARLY REPLACEMENT AND RECYCLING PROGRAMS: An Important Tool for Energy Savings and Greenhouse Gas Reductions

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Abstract

This paper summarizes a proposed program in the U.S. to stimulate replacement of older, less efficient refrigerators and permanent removal of replaced units from the grid. Ideally, this effort will be driven by utility-funded rebates, which are a proven and effective means of incentivizing consumer behavior.

Under an early replacement program, payment of rebates would require proof of both the purchase of a new appliance and the disposal of an older one. This linkage would deliver significant energy savings and GHG emission reductions. Assuming three million rebates per year over five years, an analysis of the likely benefits of these programs projects dramatic benefits:

- 43,000-85,000 GWh in total energy savings
- 30-60 MMtCO_2eq of avoided GHG emissions
- USD 5-10 billion in total energy savings to consumers

Most current rebate programs do not require both purchase and disposal, nor do they always have the necessary incentives for utilities. This proposal would leverage the Environmental Protection Agency's (EPA) pending Clean Power Plan, which will force utilities to reduce their GHG emissions. EPA is likely to allow utilities to credit reductions attributable to energy efficiency programs towards their overall targets.

By driving the replacement of less efficient older units with new, high-efficiency products, early replacement represents a cost-effective pathway to GHG reductions. The same rationale and benefits that will motivate stakeholders in the U.S. to act are relevant in other parts of the world that are seeking to increase energy efficiency and reduce carbon emissions.

Executive Summary

Based in Washington, DC, the Association of Home Appliance Manufacturers (AHAM) represents manufacturers of major, portable and floor care home appliances, as well as suppliers to the industry. AHAM's more than 150 members employ tens of thousands of people in the U.S. and produce more than 95% of the household appliances shipped for sale within the U.S. The factory shipment value of these products is more than $30 billion annually. Through its technology, employees and productivity, the industry contributes significantly to U.S. jobs and economic security.

AHAM is proposing a national Early Replacement (ER) program in the U.S. to stimulate (1) the replacement of older, less efficient refrigerators and other appliances and (2) the permanent removal of replaced units from the grid. Ideally, this effort will be driven by utility-funded rebates, which are a proven and effective means of incentivizing consumer behavior.

The AHAM proposal responds to strong interest in boosting energy efficiency and reducing emissions of greenhouse gases (GHGs). In the U.S., these goals are embodied in many state programs as well as national policies adopted by the federal government. Among these policies is the Obama Administration's proposed Clean Power Plan (CPP), a major initiative to reduce GHG emissions from the power sector that is slated to become final in the summer of 2015; under the CPP, a significant portion of these reductions would be obtained from improvements in energy efficiency.

Under an ER program as envisioned by AHAM, rebates would be paid to consumers upon proof of both the purchase of a new appliance and the disposal of an older unit. Because the older unit would be removed from the grid, operation of the new appliance would result in an immediate reduction in energy consumption. This in turn would translate into lower demand to generate electricity and therefore reduced GHG emissions from power plants burning fossil fuels.

The potential for energy savings and GHG reductions is significant because of the dramatic improvement in the efficiency of appliances over the last two decades. Refrigerators dating from the 1990s use twice as much energy as 2013 products, and products meeting the recent 2014 U.S. standards provide even more energy savings (an estimated 25 percent) compared to those produced in 2013. Making appliances more energy-efficient is a long-standing priority for AHAM members, and these gains represent a major success story for our members, consumers and government.

While achieving some positive results, existing state appliance rebate programs in the U.S. have not tapped the full potential of early replacement of older units to drive energy savings and GHG reductions. Most current rebate programs do not require both purchase and disposal, and a lack of consistency and high administrative burdens have limited program effectiveness and reduced the incentives to publicize these programs to stimulate consumer participation.

To increase incentives and maximize benefits, AHAM is proposing to leverage the CPP's call to reduce GHG emissions using energy efficiency as a major emission reduction strategy. Under the CPP, each state will have a separate emission reduction goal and will need to develop an implementation plan to meet that goal. Utilities will have significant obligations under state plans and will have a strong interest in cost-effective compliance options. AHAM has urged states and the U.S. Environmental Protection Agency (EPA) to allow utilities to credit early energy savings attributable to rebate-driven ER programs towards overall GHG reduction targets under the CPP, a step that would greatly increase incentives to conduct such programs and encourage coordinated implementation efforts at the national and regional level.

The likely benefits and costs of a well-publicized national ER program for refrigerators in the U.S. can be modeled using data and methodologies developed by the U.S. Department of Energy (DOE) and EPA, supplemented by extensive industry data. AHAM has conducted such a cost-benefit analysis for a prototype rebate program for refrigerators. Assuming a five-year program averaging 3 million rebates per year, the AHAM analysis projects GHG emission reductions of 47 million metric tons of carbon equivalent (MMtCO_2Eq), at a cost of 2.2₵/kWh. Total energy savings to consumers would be $8.9 billion, far more than outlays for rebates, which would be $1.5 billion assuming a rebate of $100 per refrigerator.

Since appliance efficiency has improved significantly around the world, the potential benefits of ER programs outside the U.S. should be comparable in magnitude to those projected by AHAM.

The success of ER programs will depend on developing strong evaluation, measurement and verification (EM&V) measures that can be used by states and utilities to track program performance and tally total energy savings and GHG reductions. AHAM is actively working toward an EM&V protocol in collaboration with DOE. This protocol would build on an established DOE decision tree for appliance rebate programs and draw on extensive government and industry data on the energy efficiency performance of old and new refrigerators, the expected service lives of products in use and the age distribution of the existing product population. Our goal is to complete development of a consensus-based EM&V protocol by the time the CPP becomes final so states can adopt it as they put together CPP implementation plans.

In sum, by driving the replacement of inefficient older units with new, high-efficiency products, ER programs represent a cost-effective pathway to GHG reductions, whether under regulatory obligation or voluntarily. The same rationale and benefits that are creating incentives for ER programs in the U.S. should command attention in other advanced economies that are seeking to increase energy efficiency and reduce carbon emissions.

I. Appliance Early Replacement – The Size of the Opportunity

The goal of ER programs is to reduce energy consumption and GHG emissions by removing millions of comparatively less efficient refrigerators and other appliances from the grid before they would otherwise be taken out of service. Replacing and recycling these older appliances offers dramatic benefits because the industry has made major product improvements, and there has been a progressive strengthening of energy efficiency requirements in DOE standards and EPA ENERGY STAR specifications. As a result, Figure 1 shows there has been a striking step-by-step increase in appliance energy efficiency since 1990:

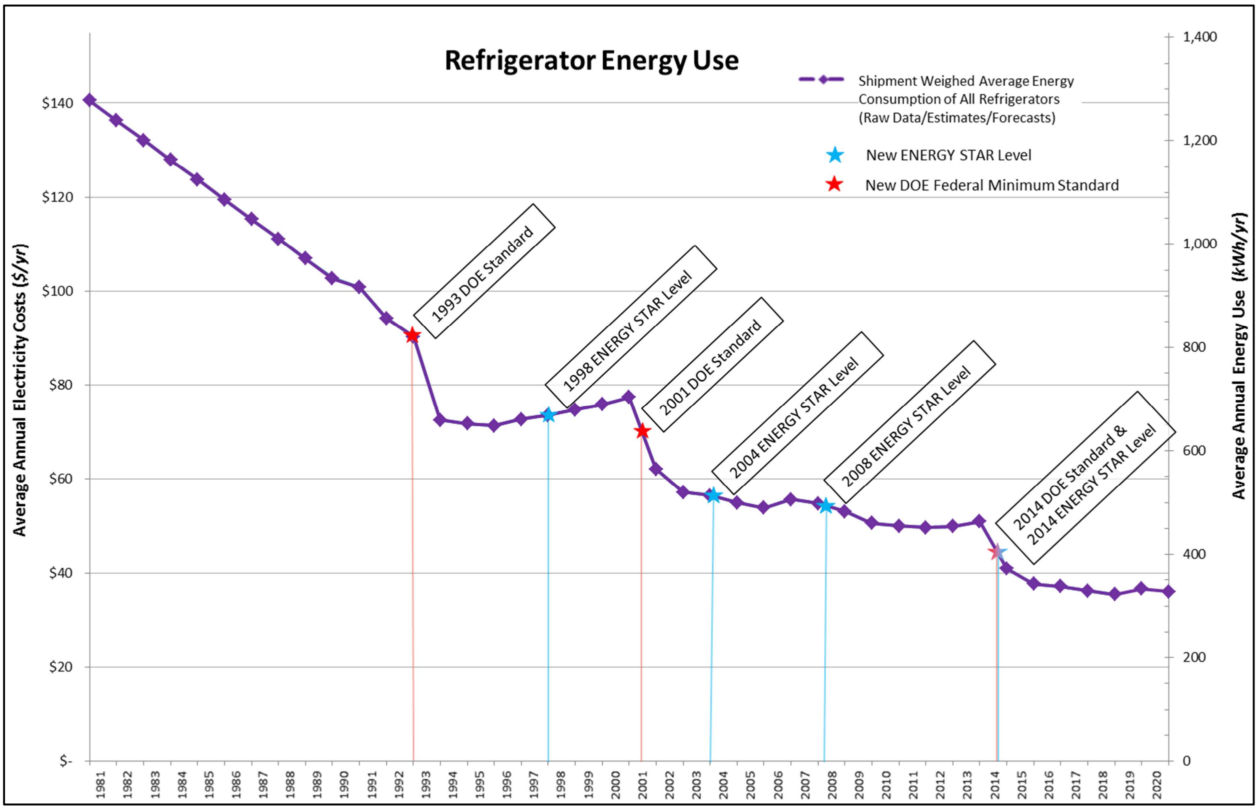

FIGURE 1: The Energy Efficiency Story: Lower Energy Use/Lower Costs to Consumers

In short, refrigerators dating from the 1990s use twice as much energy as 2013 products, and products meeting the new 2014 DOE standards will provide even more energy savings (an estimated 25 percent) compared to units produced in 2013. [1]

Because refrigerators have a long useful life and retain value for consumers, many less efficient units remain in use that do not meet the latest standards and consume significantly more energy than the newest models. In addition, less efficient units that are replaced often remain on the grid because they are kept as backup (or "basement") refrigerators, given away or refurbished and frequently resold through the secondary market.

[1] The 2014 DOE standards instituted a 25 percent reduction from the previous 2001 DOE standards for the vast majority of refrigerator product classes. Manufacturers achieved efficiency gains through incorporating technology improvements such as increased insulation thickness, vacuum insulation panels, variable anti-sweat heating, improved compressor efficiency, variable speed compressors, increased heat exchanger area, use of forced convection condenser, improved efficiency fan motors and adaptive defrost. 011-08-23 Technical Support Document for Energy Conservation Standards for Residential Refrigerators, Refrigerator-Freezers, and Freezers Section 4.3."

With 147 million refrigerators expected to be on the grid in the U.S. in 2016, replacing a significant number of units with the latest models and removing these old units will mean an immediate drop in energy consumption, translating into substantial savings for consumers and major GHG reductions.

II. Changing the Paradigm for Appliance Rebate Programs and Capturing Significantly Greater Benefits

There is strong evidence that, if well-publicized and implemented, rebate programs are an effective tool for motivating consumers to replace older refrigerators that would otherwise remain on the grid.

A noteworthy success at the federal level was under the 2009 American Recovery and Reinvestment Act (ARRA), which provided $300 million for rebates to replace older appliances. This program, which was managed by DOE and implemented through the states, resulted in 1.7 million rebates, 90 percent of which were for major appliances, including 565,000 rebates for refrigerators. DOE has lauded the program as a "huge success" and we agree.[2]

There is also an extensive track record of appliance rebate programs implemented by utilities in response to demand reduction mandates imposed by state public service commissions, often pursuant to state energy efficiency (EE) laws. These programs, too, have achieved positive results in removing inefficient refrigerators from the grid and reducing energy consumption.

A careful review of state programs, however, shows that they have not tapped into the full potential of rebates to drive energy savings and GHG reductions through the early retirement and recycling of less efficient appliances. The effectiveness of existing state programs has been limited by a number of factors:

- Methodologies for calculating and measuring benefits are not consistent across programs and jurisdictions.
- While many programs exist, there are states and regions where appliance rebates are unavailable. (By AHAM's count, only 50% of US households have access to either a purchase or disposal refrigerator rebate).
- Most programs have limited consumer recognition because they are not strongly promoted by retailers and manufacturers, likely because of the difficulty in conducting these programs on a regional rather than national basis.
- Some programs impose unnecessary and burdensome EM&V requirements that increase administrative costs and reduce the rebate amounts paid to consumers.

A more coherent and coordinated framework for rebate programs at the national level could go a long way toward addressing these limitations.

A more fundamental problem, AHAM believes, is the failure of virtually all existing programs to link purchase and disposal rebates. Our survey of state programs found that, with only a handful of exceptions, they are designed to remove older appliances from the grid or incentivize the purchase of a new product, but not to do both at the same time.[3] This lack of integration has reduced the benefits that existing programs are delivering. For example, in the case of purchase-only rebates, the utility will lack proof that the old refrigerator has been removed from the grid and thus will be unable to take credit for the energy savings of taking the old refrigerator out of service. Often, such programs condition availability of a rebate on purchase of an ENERGY STAR product, in which event the energy savings are measured as the difference in energy consumption between the new ENERGY STAR and new regular model – a small increment in actual energy use given that ENERGY STAR levels are a small percentage decrease in energy from the new DOE standards.

[2] DOE, ENER Web Posting. February 23. 2012. http://energy.gov/energysaver/articles/state-energy-efficient-appliance-rebate-program-closed
[3] A March 2014 AHAM snapshot investigation of all of the available refrigerator rebates showed only between 0.2-0.4% of households in the US have access to a linked disposal/purchase rebate.

Linking purchase and disposal rebates (i.e., requiring proof both that a new appliance has been purchased and the old unit has been removed from grid) will enable a utility to take credit for the greater efficiency increment between the new and old unit, significantly raising the energy savings and GHG reductions attributable to the rebate. By combining the disposal and purchase rebates, a single, larger rebate can be offered that drives increased consumer behavioral changes. Also, simplifying program administration reduces paperwork and other barriers to government approval of rebate programs, lowering overhead and maximizing utility dollars that flow to consumers.[4] This will result in a more favorable benefit/cost ratio, making linked rebate programs significantly more cost-effective and enhancing their attractiveness to states and utilities compared to other energy efficiency options.

A 2001 paper by the Natural Resources Defense Council supports this point, noting that, as federal efficiency standards become more stringent, "it is now difficult to save significant amounts of energy by simply persuading consumers to buy new appliances that are more efficient than the standards require." Instead, "taking inefficient older units out of service, recycling them in an environmentally sound manner, and replacing them with efficient new models . . . greatly increases energy savings and cost-effectiveness, while providing a wide range of environmental benefits."[5] This comment by NRDC was true in 2001; after the recent round of DOE energy efficiency standards, the comment has even more force now.

III. How Linked Purchase/Disposal Rebate Programs Would Work

AHAM believes certain standard design features would enhance the effectiveness of appliance rebate programs and facilitate their consistent and successful implementation on a national or regional scale. Our recommendations for a model program are below:

1. Verification. The rebate would be provided to the consumer upon verification that a new refrigerator had been purchased and the older refrigerator removed and recycled. We foresee that retailers would arrange for the pick-up of the old refrigerator when the new one is delivered, and the delivery service would complete a form documenting that the refrigerator has been removed and recycled. Upon receipt of the paperwork, a rebate check would be mailed to the consumer by the utility funding the rebate.
2. Backup Refrigerators. Some consumers may have secondary or backup refrigerators (or other appliances such as room air conditioners) that could be removed at the same time that the primary refrigerator is replaced and while an empty truck is at the home. With a modest additional rebate, consumers could be motivated to relinquish these secondary refrigerators, which could be removed and recycled for a minimal additional cost and the benefits credited to the utility funding the rebate program.
3. Rebate Amount. The amount of the rebate may need further analysis and could vary from region to region, but AHAM believes a rebate of $100 or more is likely to provide an effective incentive for purchase of new refrigerators and change consumer behavior more than current rebate levels, which are often significantly less than $100 in many state programs.[6] A

[4] As efficiency programs in the states have evolved, numerous analytical and paperwork requirements and other restrictions have been added with the goal of documenting program benefits and demonstrating cost-effectiveness. While well-intentioned, these requirements have become a collective hindrance to effective programs. Examples include requiring documentation that a recycled product is a certain age and is operational, limiting rebate eligibility to certain models, or making conservative assumptions about remaining useful life and the percentage of free riders among rebate recipients. These limitations are artificially depressing participation in rebate programs and diverting funding from incentivizing the purchase of more efficient products to unnecessary studies and verification work. This "double hit" needs to be eliminated to clear the way for more effective and broad-based rebate programs.

[5] Natural Resources Defense Council, *Out with the Old, In with the New: Why Refrigerator and Room Air Conditioner Programs Should Target Replacement to Maximize Energy Savings,* November 2001, at 3.

[6] AHAM believes that rebates at the level of $100 or more will still be a highly cost-effective option for utilities if the administrative overhead associated with many existing programs is reduced and if the GHG reductions resulting from appliance replacement and recycling provide significant CPP compliance benefits with demonstrated monetary value.

somewhat higher rebate could be offered to incentivize purchases of ENERGY STAR products.

4. Calculating Energy Savings and GHG Reductions. The energy savings and associated GHG benefits from linked purchase/recycling rebates would represent the difference in energy consumption between the new and replaced product, multiplied by the number of years that product would have remained in service in the absence of the rebate. AHAM believes that a straightforward formula is available to determine rebate-related energy savings and GHG reductions using this approach, as described below.
5. Age of Eligible Units. There should be no restriction on the age of refrigerators eligible for rebate-induced replacements. The absence of such a restriction would simplify implementation and recordkeeping and thus avoid complexity and confusion as well as reduce the significant amount of EM&V resources that are diverted from direct energy efficiency improvements to administrative requirements. It would also maximize the GHG reductions achieved: even recent model refrigerators are markedly less efficient than new 2014 models and, because of their longer remaining useful lives, their replacement will yield significant energy savings that save consumers money and reduce GHG emissions.
6. Role of DOE Standards and ENERGY STAR Levels. Consumers should be eligible for a rebate whether the refrigerator they purchase bears the ENERGY STAR label or instead complies with the latest DOE efficiency standards. The difference in efficiency on an actual annual energy use basis between DOE-compliant and ENERGY STAR products has narrowed considerably as a result of the significantly more stringent DOE standards. Maximizing consumer choice by allowing rebates for both product classes will increase the number of replaced products and produce greater overall benefits. This is because program participation will increase significantly with a broader range of products available for rebates and less complex, more inclusive eligibility criteria that encourage consumers to take advantage of these rebates. As noted above, however, purchase of higher efficiency ENERGY STAR products could still be encouraged by offering a somewhat higher rebate to purchasers of those products.
7. Duration of Program. To maximize results, annual ER rebate programs should be continued for at least five consecutive years and perhaps longer to provide a full opportunity to reach consumers who could be influenced by rebates to purchase new products. Targeted advertising and promotional activities by manufacturers, retailers and utilities would help maximize the program's impact.

IV. Estimated Benefits of Large-Scale Implementation of Purchase/Disposal Rebate Programs

AHAM has developed a cost-benefit analysis[7] of a prototype linked replacement and recycling ER program conducted on a national scale.[8] The prototype program was assumed to be five years in duration, to offer rebates of $100 per replaced refrigerator and to result in 3 million replacements per year. The AHAM analysis, which has been submitted to DOE and EPA and made available online to the general public, modeled likely reductions in energy consumption and GHG emissions resulting from the prototype program using a decision-tree approach developed by the DOE Uniform Methods Project (UMP) and EPA methodologies for converting energy savings into GHG reductions. To apply these methodologies, AHAM drew on a broad and comprehensive set of data on previous rebate programs and the age distribution and energy efficiency performance of refrigerators in service; these data derived from the published literature, DOE reports and analyses, and industry sources.

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[7] This analysis does not consider either marketing and administration costs or those for picking up and disposing of refrigerators. AHAM has been asking the US Department of Energy to convene a working group that would bring together those stakeholders with an interest and/or experience in similar rebate programs to consider how this concept might best be applied, including such considerations as marketing and administrative costs. The cost of picking up of old refrigerators we believe to be very low as the picking up can be done by the same truck that delivers the new unit. Given the metal and other recyclable content in refrigerators, disposal of an old unit is more often a source of revenue than a cost in the market-driven system that prevails in the US.

[8] AHAM Early Replacement Program Technical Support Document, available at https://aham.sharefile.com/d/s662eccbdb0d4e77a.

The costs, energy savings and GHG reductions attributable to the prototype ER program, according to the AHAM cost-benefit analysis, are as follows in Figure 2:

Weighted Average Annual Energy Savings per Unit (*kWh/unit/yr*)	588
× Average Remaining Useful Life (*years*)	5.94
= Total Energy Savings per Unit (*kWh/unit*)	3,491
Total Energy Savings from Program (*GWh*)	52,368
Total Carbon Reduction from Program (*MMtCO$_2$*)	36.11
Total Cost of Rebates (*$ million*)	$1,500
Cost of Avoided Carbon Emissions (*$/MtCO$_2$*)	**$41.54**
Program Rebate Cost (*$/kWh*)	**$0.0286**
Program Savings to Customers (*$ million*)	$6,792
Benefit to Cost Ratio	4.53

Figure 2: AHAM Early Replacement Program Results

These projections confirm that large-scale implementation of refrigerator replacement programs on the AHAM model will be a highly cost-effective tool for reducing energy consumption and GHG emissions, with benefits greatly exceeding the costs.

Importantly, AHAM's methodology to model the benefits of ER programs was designed to capture only energy savings and GHG reductions that are directly induced by rebates and to exclude "business as usual" savings that would occur because of normal product turnover in the marketplace. Thus, "free riders" who would purchase a new product with or without the rebate are not counted. As explained in AHAM cost-benefit analysis, this calculation was performed by expanding the methodology used by DOE in its Uniform Methods Program (UMP) protocol for determining free ridership in rebate-driven refrigerator recycling programs and taking into account several studies of free ridership in state rebate programs.

While the main driver for ER programs would be achieving energy savings and GHG reductions, other benefits will be realized as well. First, consumers would see declines in their electricity bills that would increase their purchasing power. Second, reductions in power generation from lower electricity consumption would translate into declining emissions of conventional pollutants and thus lower ambient levels of particulate matter (PM), nitrogen oxides (NO_x) and sulfur dioxide (SO_2), which are associated with known health effects and result in medical costs from mortality and disease. As described in the AHAM cost-benefit analysis, SO_2 and NO_x emissions would be reduced by nearly 18 million pounds and 32 million pounds, respectively, resulting in avoided adverse health effects valued at $715-$1,436 million. Finally, because of the increased consumer demand for new appliances, the program will boost manufacturing output and retail activity, with accompanying growth in jobs.

V. <u>Leveraging the Clean Power Plan to Incentivize Effective ER Programs</u>

The CPP is the cornerstone of the Obama Administration's initiatives to address climate change. Based on section 111(d) of the federal Clean Air Act (CAA), the CPP targets a 30 percent reduction in power plant GHG emissions by 2030 compared to 2005 levels. As the federal agency charged with carrying out the CAA, EPA is the architect of the CPP and will be responsible for implementing it. EPA proposed the CPP in June of 2014[9] and, after receiving extensive comments from the public, is working toward a final version, expected in the summer of 2015.

As required by CAA section 111(d), the CPP proposal identifies the Best System of Emission Reduction (BSER) for GHG pollution from fossil-fueled power plants and the level of emissions improvement that this system is capable of achieving. Based on its BSER determination, the proposal then sets interim and final emission rate reduction goals for each state. When the CPP becomes final, states will be responsible for developing implementation plans to meet these goals. The CPP is designed to give states flexibility in selecting the mix of policies and incentives included in their plans, providing these tools will deliver the reductions required to attain the state goal.

The proposed CPP identifies four key “building blocks” that, in EPA’s judgment, represent BSER and, if implemented by the states, will be sufficient to meet their emission reduction goals. (Building Block 4 is focused on increasing end-user energy efficiency). Based on the ability of states to strengthen existing demand reduction (DR) programs and adopt EE best practices, EPA predicts that this Building Block 4 will reduce electricity consumption by approximately 1.5% per year starting in 2017, with cumulative energy savings of 10.7 percent by 2030.

EPA’s selection of EE as one of the four critical CPP Building Blocks recognizes that lowering electricity use is a proven, cost-effective strategy for reducing power plant GHG emissions that provides tangible monetary benefits to consumers while lowering carbon pollution. It also recognizes that, while some state EE programs have achieved substantial progress, there are significant untapped opportunities to enhance efficiency that can be captured through more ambitious and innovative programs. By targeting a national reduction in demand of 10.7% by 2030, the CPP will challenge states and utilities to strengthen EE programs while preserving their flexibility to select the approaches that work best in particular circumstances.

A comprehensive, rebate-driven initiative to replace older, less efficient refrigerators and other appliances and remove them from the grid would enable states and utilities to significantly boost energy savings and GHG emission reductions and thus would make a major contribution to the CPP’s EE goals. States would undoubtedly consider other EE strategies as well, but the high cost-effectiveness and large benefits of ER programs should be selling points to states and utilities looking for the most effective compliance tools. By enabling states and utilities to credit energy savings from ER programs toward overall GHG reduction targets, the CPP should greatly increase incentives to conduct such programs and encourage coordinated implementation efforts at the national and regional level.

The CPP as proposed would not take effect until 2020, when states would need to begin to meet “interim” goals, which would become progressively more stringent as the final compliance date of 2030 approaches. The availability of “credits for early action” could help jumpstart ER programs and other initiatives to reduce power sector emissions in advance of the 2020 compliance date. EPA has indicated[10] that the Agency is favorably inclined toward allowing such credits – i.e., permitting emission reduction actions taken after 2014 but before 2020 to count toward 2020-2029 interim goals and 2030 final goals – and AHAM has supported this approach.

The value of early action credits is particularly compelling for ER programs, which can be scaled-up quickly, achieve GHG reductions immediately and deliver tangible multi-year savings in energy costs to consumers. If EPA establishes a mechanism for early action credits, this will increase incentives to launch ER programs (ideally under a national umbrella) as early as 2016 to generate credits that can be applied toward 2020 interim targets.

VI. Establishing EM&V Measures for ER Programs

[9] 79 Federal Register 34830 (June 18, 2014).
[10] 79 Federal Register 64543, 64545-6 (October 30, 2014).

Environmental and utility regulators in the U.S. typically require that energy efficiency programs conducted to meet regulatory requirements include approvable measures for quantifying, monitoring and verifying program effectiveness and benefits. These measures are then incorporated in an Evaluation, Monitoring and Verification (EM&V) plan that establishes a protocol for tracking energy efficiency results. If linked purchase/disposal ER programs are to become more prevalent under the CPP or otherwise, broadly accepted EM&V measures will be essential so that regulators and utilities have confidence that they will receive credit for the energy savings and GHG reductions achieved.

The decision-tree approach underlying the AHAM cost-benefit analysis creates a solid foundation for developing such EM&V measures. The decision-tree provides a step-by-step process for determining "average" per unit energy savings for refrigerators removed from the grid in response to rebates. To apply the decision-tree, extensive data are available on the energy efficiency performance of old and new refrigerators, the expected service lives of products in use and the age distribution of the existing product population. In addition, the appliance rebate program conducted under the 2009 stimulus legislation provides an extensive database on how consumers respond to rebates for these products. As a result of these multiple data sources, the energy savings and GHG reductions achieved by these programs are quantifiable with confidence. As discussed above, it also is possible to reliably account for "free riders" and exclude them from the calculation of program benefits.

In addition, a documentation system can be readily devised to assure that replaced refrigerators are recycled and disconnected from the grid. A format for tracking program performance and effectiveness and reporting results should likewise be relatively straightforward to develop.

AHAM is working with DOE officials on a process to develop a set of standardized and validated EM&V measures supported by key stakeholders and EPA/DOE. Such an "off the shelf" ER protocol with standardized EM&V measures would provide assurance that these programs will deliver documented GHG reductions for which states and utilities can take credit under the CPP or other EE initiatives.

VII. <u>Conclusion</u>

By driving the replacement of inefficient older units with new, high-efficiency products, ER programs represent a cost-effective pathway to GHG reductions, whether under regulatory obligation or voluntarily. The approach proposed here is consistent with many existing programs in the U.S., but it could be adopted anywhere and adapted to meet local requirements. The goals of EE and GHG reduction are the same. The analysis performed by AHAM demonstrates that these programs have the potential to achieve dramatic energy savings for consumers and substantially reduced carbon pollution as lower demand for electricity results in declining emissions by fossil-fuel power plants. The outlays for rebates under these programs are projected to be small relative to the benefits achieved, a strong selling point for regulators and utilities looking for the lowest cost emission reduction strategies.

While AHAM's initial focus has been on refrigerators, the early replacement/recycling model is equally applicable to other appliance classes (e.g., dishwashers, clothes washers, dryers, and room air conditioners), and their inclusion would yield sizable additional reductions in energy consumption and GHG emissions.

Interest in improving the effectiveness of energy efficiency is strong in the U.S. both because of state mandates to reduce electricity demand and a heightened national focus on reducing GHG emissions, epitomized by the Obama Administration's proposed Clean Power Plan. AHAM has advocated ER programs as a valuable tool to meet the CPP's goal of lowering emissions by enhancing state EE initiatives. We expect that interest in these programs will increase significantly if states and utilities are confident that the energy savings they achieve can be fully credited toward state emission reduction targets under the CPP. To that end, AHAM is collaborating with DOE to develop a standardized set of EM&V measures that could be broadly adopted with a high likelihood of regulatory acceptance.

Although the U.S. situation is unique in certain respects, the same basic drivers for greater energy efficiency are prevalent in other parts of the world. These include the dramatic strides in improving appliance energy efficiency achieved by industry in response to government standards, the interest of regulators and the public in continued reductions in energy consumption and the demand to lower carbon pollution in response to climate change concerns. Thus, the ER model should be worthy of serious consideration by industry and government outside the U.S. although the differences in regulatory systems may dictate different incentives and methods of implementation.

Innovation in Residential Energy Efficiency Programs – The Power of Big Data and Closed-Loop Marketing

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Enervee

Abstract

Consumer appliances and electronics are a major focus of energy efficiency initiatives, from standard setting and labeling programs to large-scale, expensive efforts to incentivize consumers to choose the most efficient products. As a whole, however, these efforts are not as cost-effective as they could be: In the USA, while many programs have achieved significant kWh savings, they do so in an expensive, cumbersome manner, with relatively poor levels of engagement by consumers and challenging, estimation-filled measurement and evaluation processes. Using the abundance of available online data on everything from product efficiency to energy sources and costs to consumer purchasing behavior can help create a simpler, more accurate and more engaging path to efficient product sales. This paper will discuss the ways that big-data analysis and closed-loop digital marketing can streamline the design, marketing, implementation and evaluation of consumer product efficiency programs. Results of the new approach will be shared from recent pilots with investor owned and municipal US electric utilities.

Challenges Facing Utilities and Governments

The leading utility energy efficiency programs in the United States have done a remarkable job of meeting regulatory energy saving requirements, while improving results. At an average of $0.028/kWh, electric utility energy efficiency programs are less than half the cost of alternative new electricity resource options [1]. Programs to replace inefficient incandescent light bulbs with compact fluorescent lamps were the mainstay of residential programs over the past decade, but the mandatory lighting performance standards that came into effect in the 2012-14 period, along with more stringent building codes, are forcing utilities to look elsewhere for cost-effective savings, particularly as regulators seek larger end-use efficiency gains going forward.

Innovation is critical to address the myriad challenges facing utility efficiency program administrators [2], including the need to:

- Increase participation in appliance and electronics programs beyond lighting
- Achieve greater energy savings per participant
- Respond to the increase in online product research and shopping trends
- Provide customers with actionable information, including objective product recommendations
- Offer cutting-edge engagement to electronics-dependent customers
- Target marketing to achieve superior energy savings for each dollar spent
- Streamline the process of tracking and validating savings claims.

Meanwhile, governments are struggling to find the resources to establish impactful standard & label programs – and maintain proper oversight. Even governments that have advanced S&L schemes, like the European Union and Member States, may lack public product databases and the means of ensuring compliance with legal requirements. And it is challenging for governments to make actionable information available to consumers in a user-friendly manner.

Driving Innovation in Residential Efficiency Programs

For the past decade, US-based utilities have mostly focused their residential appliance energy efficiency programs on providing marketing and field services directly at brick and mortar stores. As the majority of consumers now use the Internet and mobile phones to research products before going into stores, there is a need to engage consumers during this early shopping consideration phase.

This also presents a golden opportunity to unleash the power of the pocketbook, by presenting truly actionable information that consumers need to make resource-smart purchase decisions. Enervee's product efficiency data and marketing platform uses real-time data from manufacturers and national retailers and allows personalization by utility rate and usage profile. This fully digital approach brings well-proven tools to improve customer targeting, tracking and engagement to the energy efficiency industry for the first time. The rest of the paper expands on these game-changing capabilities and offers insights gained from early application in the USA and other countries.

The Enervee Big Data Engine – A New Source of Real-Time Market Intelligence

Enervee's services derive from a data engine that currently provides information on the following off-the-shelf consumer product categories:

- Appliances (refrigerators, freezers, dishwashers, clothes washers, clothes dryers)
- HVAC equipment (air conditioners, boilers, furnaces, gas & electric water heaters)
- Electronics (televisions, game consoles, tablets, computer monitors, projectors)
- Replacement light bulbs
- Water fixtures (faucets, showerheads, toilets)

A large amount of data is collected daily (Figure 1). At present, Enervee sources over half a million product offers and one hundred thousand energy profiles for the US market daily, as well as information on utility incentives and utility rates. The raw data undergo quality assurance, and the different types of data are matched by individual product model number. Key product metrics (retail price, energy efficiency, market share) are archived for future reference. Clients doing cutting-edge energy efficiency and regulatory work (such as standard-setting) have begun to subscribe to product data feeds for use in their research.

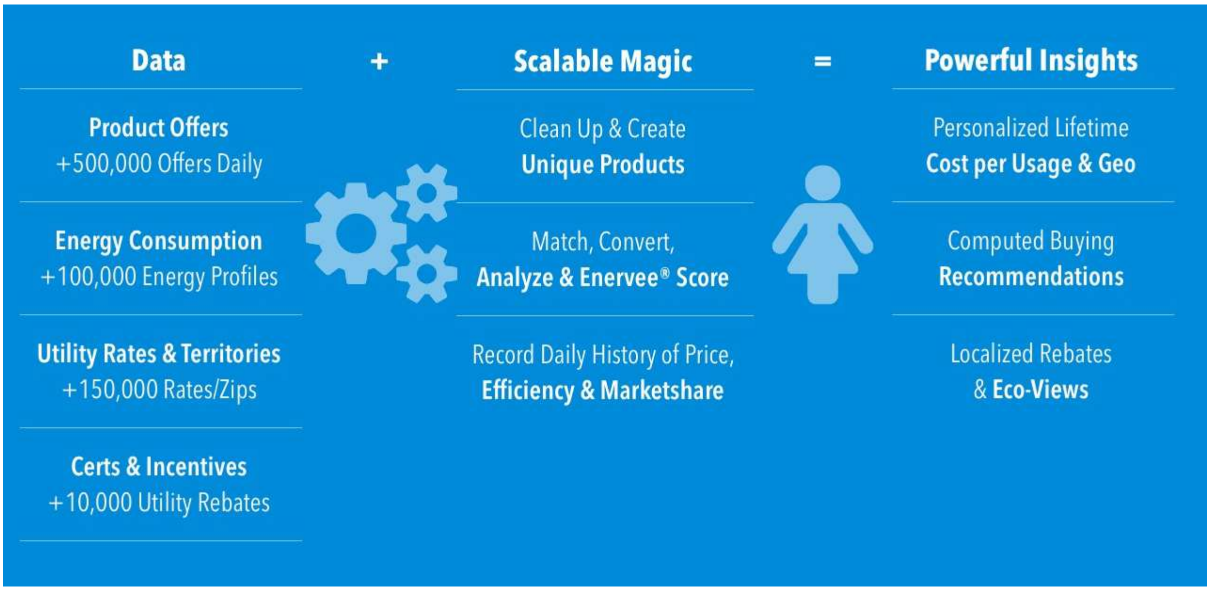

Figure 1. Enervee Big Data Engine – Actionable, Real-Time Insights

Sophisticated data analytics can improve efficiency program design. Among the unique capabilities of the platform is the ability to extrapolate sales data in real time by capturing online sales indicators shared by major retailing sites including Best Buy and Amazon. The algorithm was created through an analysis of the correlation between online and in-store sales conducted for Enervee by researchers at the Lawrence Berkeley National Laboratory. With deep data analysis, utilities can identify prime opportunities to conserve resources, create new incentive programs, target market segments for special promotions, and forecast program results in real time. Enervee can also provide new insights into the behavior, motivation, demographics, and affinities of utilities' customer bases that can help scale programs and improve customer engagement.

This new source of real-time market data, combined with other data (e.g., personalized electricity price) and related closed loop marketing, verification and analytical capabilities, presents opportunities to significantly improve upon existing efforts to speed the uptake of super-efficient products by the mass market.

The Enervee Score – Making Efficiency Visible to the Untrained Eye

It is becoming clear from our longitudinal cache of daily market intelligence that lack of market transparency is a critical barrier to market transformation that has not been fully overcome by existing standard & label schemes. What we are finding is that in many product categories, there is a wide range in efficiencies and prices - with quite efficient products capable of delivering the lowest total cost of ownership, or even lowest up-front purchase price. The key barrier in these cases may not be incremental up-front cost, but rather lack of access to actionable information.

Enervee has therefore collaborated with experts from Lawrence Berkeley National Laboratory, TopTen USA, Ecova, and the American Council for an Energy Efficient Economy to develop the Enervee Score (Figure 2), which is calculated for each product model. The Enervee Score ranks the efficiency of individual product models within a given product category (such as dishwashers) on a scale of 0 to 100. The higher the Enervee Score, the more efficient the model relative to all models with comparable size/capacity. We have broken the Enervee Score into four efficiency levels, with new models currently offered for sale falling with the 50 to 100 range.

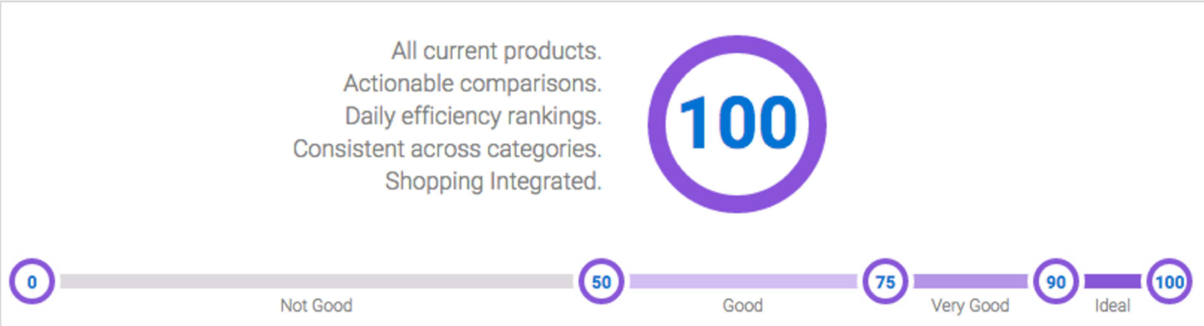

Figure 2. The Enervee Score – Actionable Energy Efficiency

Products with scores below 50 represent the current stock of models that are less efficient than the worst new models sold today, like a 10-year-old refrigerator or a used TV offered for sale in the classifieds. Enervee scores may reflect energy efficiency, water efficiency or a combination of the two. The basic methodology for determining the Enervee Score is a three-step process that scores individual product models, based on deviations from predicted values determined by regression analysis. The Enervee Score is dynamic, meaning that it is updated daily for all products, based on the range of new products currently available on the market.

By translating technical efficiency metrics into a universally understood 0 to 100 scale, the Enervee Score empowers any consumer to consider energy and water efficiency as they comparison shop, along with other selection criteria, such as price, reviews or features. Leading utilities in the USA are integrating the Enervee Score into customer marketplaces to support the customer shopping journey, as described in the utility case studies.

Applying Closed-Loop Marketing Techniques to Transform Markets

The customer journey for plug loads and appliances (PLA) has grown more complex, with a major shift in habits over the past five years to include online research and shopping. As a result, marketers have expanded on the traditional 3-step mental model of marketing – stimulus, first moment of truth (in store), second moment of truth (post-purchase user experience) – to include pre-shopping, for which the moniker ZMOT (zero moment of truth) has been coined [3].

A recent survey of 500 people who had made an electronics purchase within the past two months showed that personal technology products are a very considered purchase [4]: Over half of the respondents said that they had taken a month or more to make their purchase decision, from the time when they first decided to buy in the category. The study also showed that the average shopper used more than 14 sources of information to arrive at their decision, while younger shoppers between the ages of 18 and 34 used 50% more sources than the average. The results also show that ZMOT sources are more widely used than stimulus and in-store sources, with nearly 90% of shoppers engaging in multiple ZMOT activities (e.g., search, comparison website, brand and retailer websites).

Closed-loop marketing is a way of engaging and tracking customer engagement from initial purchase consideration all the way through completing the transaction. Data is collected throughout all stages of interaction, with a continuous improvement cycle to optimize the marketing efforts based on enhanced knowledge about the customer and his/her preferences. Enervee's closed-loop marketing program identifies utility customers as they begin their shopping journeys online and stays with them through purchase, incentive delivery and repeat redemption, taking full advantage of the targeting and cost-saving potential of the web (Figure 3).

Figure 3. Closed-Loop Commerce Platform for In-Market Shoppers

Enervee is applying today's digital marketing best practices to execute turnkey closed loop programs for utilities in the United States. The following section provides some examples. The basic approach is to target and acquire in-market customers with the greatest potential for making a purchase, reaching them with multiple messages promoting efficiency. In parallel, the utilities offer consumer incentives, which Enervee can deliver in several ways (e.g., prepaid card, PayPal, rewards). Enervee seeks to leverage participant acquisition cost by creating a customer relationship that drives recurring energy efficiency savings, instead of just a one-time rebate transaction.

The closed-loop system also provides opportunities to explore new incentive program design and assess their cost-effectiveness, as well as to streamline the process of validating energy saving claims. Detailed reporting and analytics can be automated and customized.

Utility Marketplaces in the USA

Utility rebate programs are the most common type of residential energy efficiency incentive program in the USA [5]. By micro-targeting these incentives using the latest digital marketing techniques and providing shoppers with actionable information that empowers them to make energy-smart choices, it is possible to greatly increase the scale of efficiency programs. New incentive designs such as sweepstakes may also increase cost effectiveness by reducing the price per delivered incentive.

Overview of Utility Offering

As of July 2015, Enervee serves leading utilities in the USA with a combined customer base of over 7.9 million households. Utilities typically opt for a comprehensive suite of products and services that function in concert with each other:

- **Online Marketplace –** a white labeled utility shopping platform (Figure 4) that enables consumers to compare the latest appliance and electronics products. It provides information on the energy efficiency score, energy savings, aggregated user review rating, purchase price, where to buy and recommendations for more popular or affordable similar models.

- **Closed-loop Marketing –** running of large-scale geo-targeted digital advertising campaigns using paid search, paid social and retargeting to drive in-market shoppers to the online marketplace.

- **Incentive Processing –** enabling an online application for submitting rebates/incentives with digital purchase verification and fulfillment of payment directly to customer via a Visa prepaid debit card or transfer to bank account using PayPal.

- **Data Analysis and Reporting -** a deep dive into what the market penetration of energy efficient appliances is in a specific geography and recommendations on where the opportunities are for shifting consumers to purchase more energy efficient products.

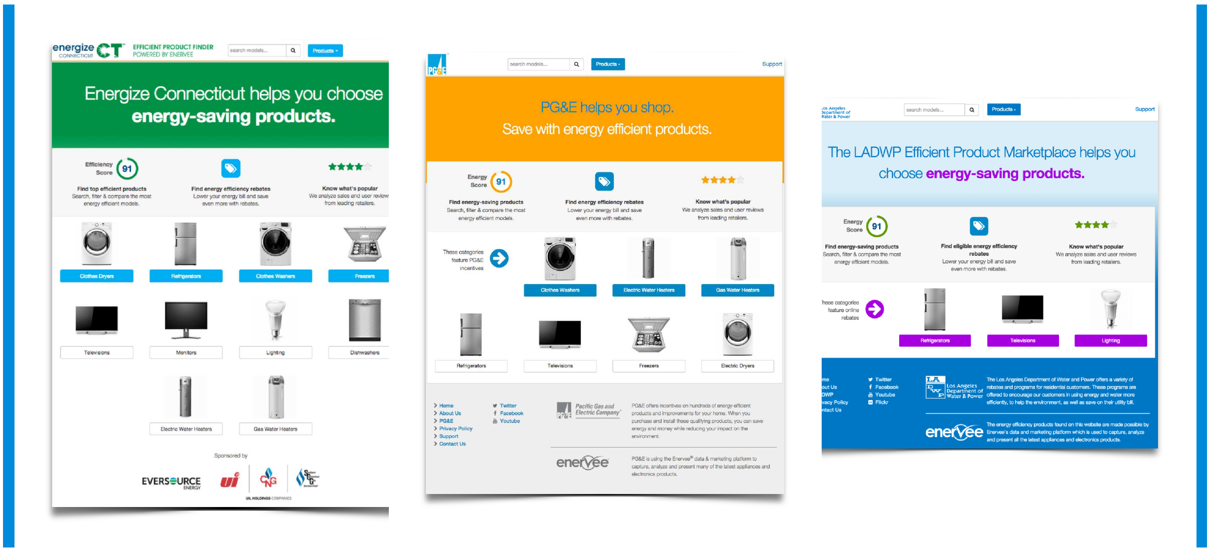

Figure 4. Energize CT's Efficient Product Finder, PG&E's Energy Smart Marketplace and LADWP's Efficient Product Marketplace

Preliminary Insights

We are beginning to study initial results from Enervee market intelligence and utility marketplace analytics, and we provide several examples here. Figure 5 suggests that the product models that people choose to view on the utility marketplaces are more efficient than what the marketplace has to offer. The efficiency metric for clothes washers is a modified energy factor (MEF), which takes into account machine electrical energy consumption, hot water energy consumption, the energy required for removal of the remaining moisture in the wash load, and the combined low-power mode energy consumption. The higher the MEF value, the more efficient the clothes washer is. Figure 5 shows the MEF for the individual clothes washer models that people chose to view on the PG&E Energy Smart Marketplace, compared with the weighted average for all models offered for sale via Amazon, estimated from sales rank. From Google Analytics and our model data, we can calculate the weighted average laundry capacity and MEF of the washer models that people click on first (the chart shows averages for the models viewed within the first four pageviews). The results show that washers viewed on the marketplace are roughly 20% more efficient, despite the fact that some have a larger capacity. The pageview data are based on in-market shoppers landing on the Energy Smart Marketplace through organic searches and digital ads, with no direct marketing to customers coming from PG&E. This suggests that if we can drive people to marketplaces with actionable information, chances are better that they will search for – and may ultimately purchase – a more efficient product model.

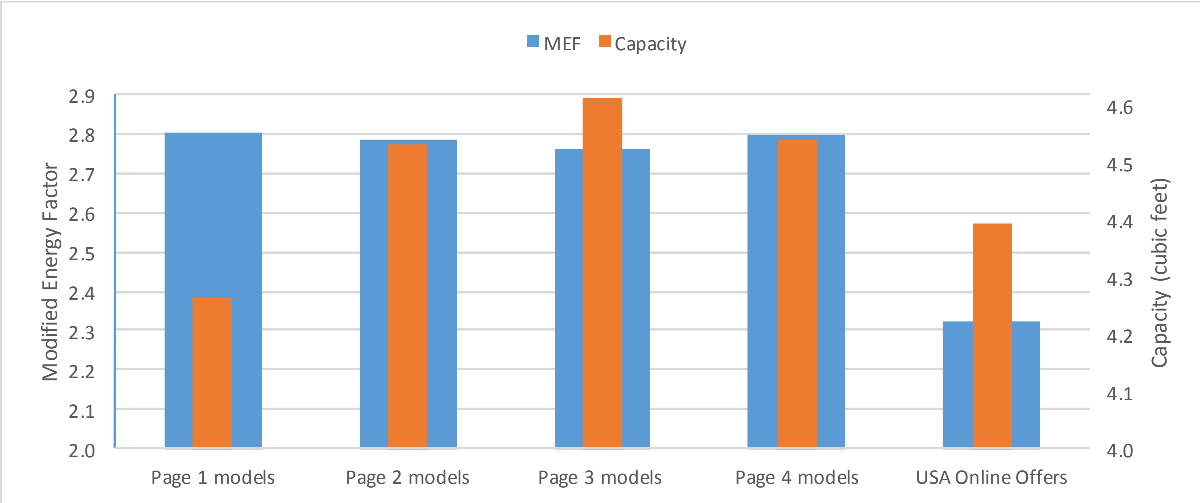

Figure 5. Energy Efficiency of Clothes Washers Viewed on PG&E Energy Smart Marketplace vs. US National Average

Sweepstakes can stimulate engagement with the marketplace, as demonstrated under a 1-month clothes dryer sweepstakes conducted for one of our utility clients (Figure 6). The marketplace, combined with a series of monthly sweepstakes, is demonstrating encouraging results, with a dramatic increase in customer engagement, from more time spend viewing marketplace information to a doubling of rebate opt-ins. Given that the sweepstakes did not target in-market shoppers, the slight decrease in conversion rate is to be expected.

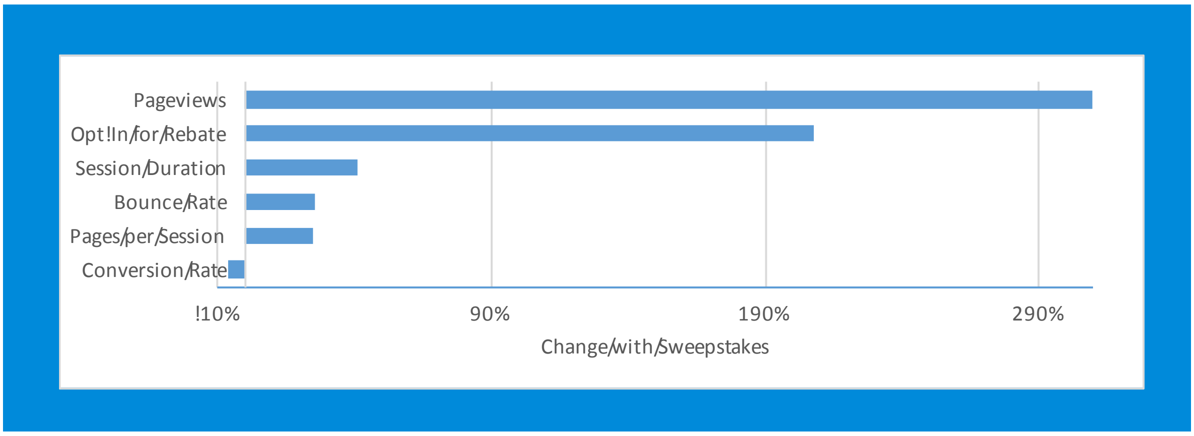

Figure 6. Change in On-Site Engagement During Dryer Sweepstakes (May-June 2015)

These preliminary results from utility marketplaces powered by Enervee are promising, albeit to a certain extent anecdotal, given the novelty of the marketplace approach. Enervee is eager to partner on research to make use of our real-time market intelligence to better understand market dynamics and the effectiveness of efforts to transform markets, including our utility marketplaces and closed-loop marketing programs. We are currently participating in number of studies:

- A utility study conducted by a third party contractor to map out the program logic, appropriate program metrics and processes involved in providing actionable information to shoppers;
- A government study comparing Enervee market data with that from other sources;
- A study conducted jointly with a university research team to examine how the framing of energy information may impact clients' purchase decisions during their online shopping of appliances.

Broader Implications of Real-Time Data and Closed-Loop Marketing

There are good prospects for innovative residential energy efficiency programs to achieve large energy savings going forward. It has been estimated that next generation energy efficiency programs in the USA could cut projected electricity consumption through 2030 by 27% and natural gas consumption by 19%, with the residential sector contributing 36% (417 TWh) of the electricity savings and 53% (997 TBtu) of the natural gas savings [2].

By providing affordable, real-time market surveillance and data analytics, the big data and marketing platform described above has the potential to modernize and improve the performance of emerging technology, energy efficiency and codes & standards programs operating across the market transformation continuum, as summarized in Table 1.

Table 1. Application of Real-Time Consumer Product Data to Residential Programs

<table>
<tr><th>Data & Related Services</th><th>Codes & Standards Programs</th><th>Energy Efficiency Programs</th><th>Emerging Technology Programs</th></tr>
<tr><td>Energy performance data by model and market</td><td>Optimizing level of stringency, in light of installed base, new product sales trends and best commercially available technology</td><td rowspan="4">Program optimization through better market data, geotargeting & automation (e.g., dynamic product eligibility, automated online verification of rebate eligibility)
New, personalized tools to support multi-channel shopping journey and change purchasing behavior
Improved monitoring & verification</td><td rowspan="4">Analysis of market transformation dynamics
Technology assessments</td></tr>
<tr><td>Retail sales price & personalized total cost of ownership estimates</td><td>Estimating Impacts of regulatory changes</td></tr>
<tr><td>Product market share estimates and availability by retailer</td><td>Automated compliance checking</td></tr>
<tr><td>Closed-loop marketing capabilities</td><td></td></tr>
</table>

In the context of **emerging technology programs**, the availability of real-time market data by product model number presents a treasure trove of information to better understand the dynamics of commercializing new, super-efficient consumer products. For the first time, it is possible to track efficient product market trends at high resolution over time and apply automated statistical analysis. The available market intelligence would contribute, for example, to achieving the goals of California's Statewide Emerging Technologies Program by providing input into technology assessments and/or assessments of market acceptance. Insights from geo-targeted, long tail, closed-loop digital marketing programs can also inform theory development and policy research related to changing purchasing behavior.

Those who design, implement and oversee **energy efficiency programs** can also benefit in many ways from affordable access to real-time consumer product market data and closed-loop marketing capabilities. Incentives offered direct to consumers can be dynamically updated to reflect product-specific market developments and opportunities – and efficiencies can also be achieved through automation of verification, issuance of rewards (e.g., pre-paid credit cards) and monitoring tasks. As new, super-efficient products reach the marketplace, for example, downstream rebates can be dynamically shifted to the cutting edge products for greatest impact. In general, program design can be improved to deliver the right incentives to the right market actors to overcome product-specific barriers to the largest savings opportunities – as they evolve over time. Closed-loop marketing programs can be highly cost-effective, due to lower-cost acquisition, effective engagement during the shopping journey, improved conversion and monitoring, and opportunities to increase retention.

An important consideration in determining initial energy performance criteria or updating **codes & standards** is ensuring that the more efficient consumer product/equipment will be cost-effective (i.e., provides a net fiscal benefit) to consumers, while yielding societal benefits (e.g., reduced greenhouse gas and air pollution emissions, improved environmental quality, enhanced supply reliability). Real-time market data on the efficiency of product models, together with data on their total cost of ownership and estimates of market share of new sales by model, offer valuable inputs into the analytical work underlying such rulemaking proceedings. Experts in Europe have been calling for a systematic region-wide monitoring of sales for key products [6] – and now this can be readily achieved, using Enervee's cost-effective, real-time data engine. In addition, the data platform paves the way for automated compliance checking. In California, for example, manufacturers of federally and State-regulated appliances are required to certify their appliance efficiency data and other information to the California Energy Commission. All products offered for sale can be cross-checked daily by individual model number against the CEC's online database of certified products to ensure that they have been duly certified. This capability could facilitate the CEC in its task of assessing administrative civil penalties (which, for example, must consider the length of time over which the violation occurred). The recent G7 Hamburg Initiative for Sustainable Energy Security communique stated that the G7 and European Commission will explore the establishment of energy-related product data bases that enhance transparency in product energy efficiency, opening the door for innovation in Europe, as well.

Increased market transparency also facilitates **market transformation beyond the scope of dedicated MT programs**. Green procurement officers wishing to set ambitious benchmarks, for example, can readily assess market availability and price, relative to energy benefits. Work with manufacturers is another example: Sony's Environment and Technology Compliance department collaborated with Enervee to develop a comprehensive performance rating system for gaming consoles such as PS4, Xbox One and Wii U.

Closed-loop marketing can be applied beyond US markets and does not require efficient programs funded by utilities. The same model could be used in any economy with high internet and e-commerce penetration. Enervee has worked on a range of initiatives with international government clients that rely on our big data engine, including:

- Conducting pricing, energy efficiency market share and compliance monitoring for appliances and electronics.
- Developed an appliance database and calculated an energy use and CO_2 emissions baseline for the S&L program, building on work done for the Clean Energy Ministerial Super-Efficient Appliance Deployment initiative to create a global data framework for product energy efficiency [7].
- Analyzing the recent and historical product energy efficiency and life-cycle cost improvement in national appliance markets.

Big data and closed-loop marketing are poised to play a critical role in achieving residential energy efficiency targets. While Table 1 demonstrates the utility of new big data capabilities for a wide range of market transformation programs, it is the combination with multi-channel, closed-loop marketing that promises a quantum leap in the **effectiveness of programs to change purchasing behavior**. Holistic programs that appeal to consumers through information, economic incentives, and social interaction are likely to achieve the greatest impact [8]. Together with leading utilities, regulators, governments, retailers, and manufacturers, Enervee's product efficiency data engine and related services are ushering in a new era of energy-smart shopping, unleashing the power of the pocketbook to drive efficiency.

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Commercial and Professional Refrigeration Products: Promoting Energy Efficiency with Legislation, Empowered Stakeholders and Rebates

Eva Geilinger, Eric Bush

Topten International Services

Abstract

Commercial and professional plug-in refrigerated cabinets use much more energy than household products. Saving potentials are huge but there are barriers to improving efficiency. Standardised declaration of energy consumption does not exist; this makes comparing the electricity costs of products impossible. Coming EU legislation will overcome this lack of basic information. How effective the new legislation will be depends on the outcome of the ongoing draft and revision process. A rebate programme for efficient refrigerated cabinets in Switzerland and the European Horizon 2020 project "ProCold" work to empower market participants and overcome barriers to developing efficiency.

Introduction

Based on estimates for the year 2016, plug-in commercial and professional refrigerated cabinets use half as much energy compared to household refrigerators and freezers in the EU, even though there are 12 times less commercial / professional cabinets than household products (commercial / professional: >25 million units and >43 TWh/year[1] [1], household: 304 million units and 84 TWh/year [2]). Size and cooling capacity notwithstanding, the main reason commercial and professional cabinets use so much energy is that they are not energy efficient. Household refrigerating appliances have improved tremendously over the past 20 years thanks to the EU energy label and ecodesign requirements. In 1995, when the EU energy label for household refrigerating appliances was introduced, class G products were common. At present no refrigerator or freezer worse than class A+ can be introduced to the market[2]. Energy consumption was successfully reduced by more than 70% (for models with same size). The best products in class A+++ are twice as efficient as A+.

Energy consumption of plug-in commercial and professional refrigerated cabinets can easily be halved with best-available-technology products. This would bring energy savings of >20 TWh/year and save 4 billion Euros in electricity costs (at an electricity rate of 0.2 Euro/kWh). It is not only the direct users (retail, gastronomy etc.) but every market participant that gains from better energy efficiency:

- green procurement can help public authorities and private businesses reach their environmental targets and reduce spending
- the food and beverage industry can bring savings to their customers by buying efficient cabinets
- manufacturers and suppliers benefit from the higher value and purchase prices of energy efficient products while total costs for their customers are reduced

The coming chapters will discuss saving potentials, barriers to improving energy efficiency and three initiatives to overcome them: a rebate programme for efficient refrigerated cabinets in Switzerland, the European Horizon 2020 project "ProCold" empowering market participants, and coming EU legislation.

[1] Estimates by Topten based on ecodesign preparatory studies and own research

[2] Exemptions include wine storage appliances, absorption-type and thermoelectric products

Saving potentials

The introduction noted an astounding difference in energy consumption between household and commercial/professional products. Figure 1 (below) illustrates this discrepancy. It depicts consumption values found in catalogues (not standardised). The EU labelling classes for household refrigerating appliances are shown for comparison. Consumption of commercial/professional products lays way outside the scale of household products. There is huge potential to improve.

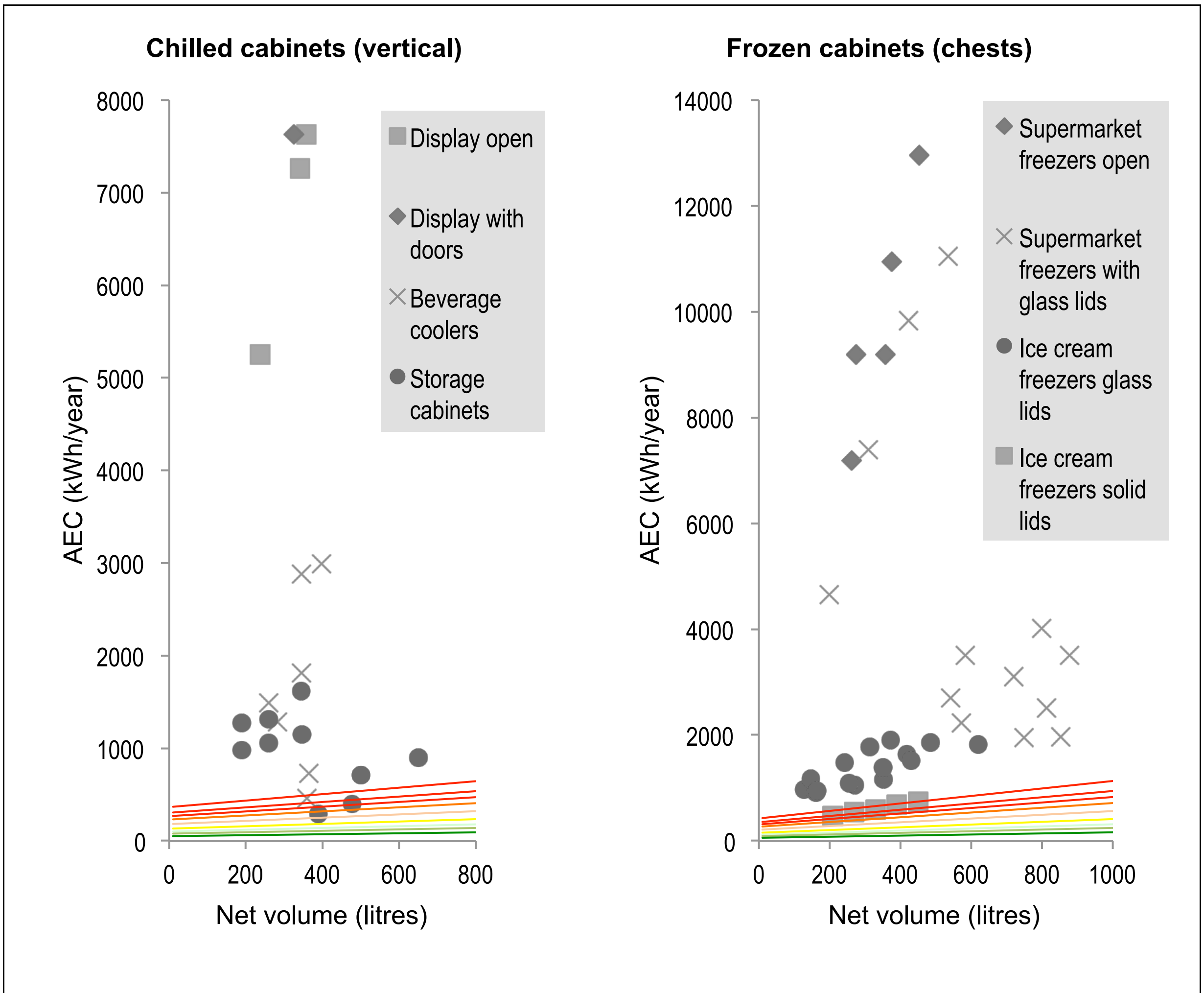
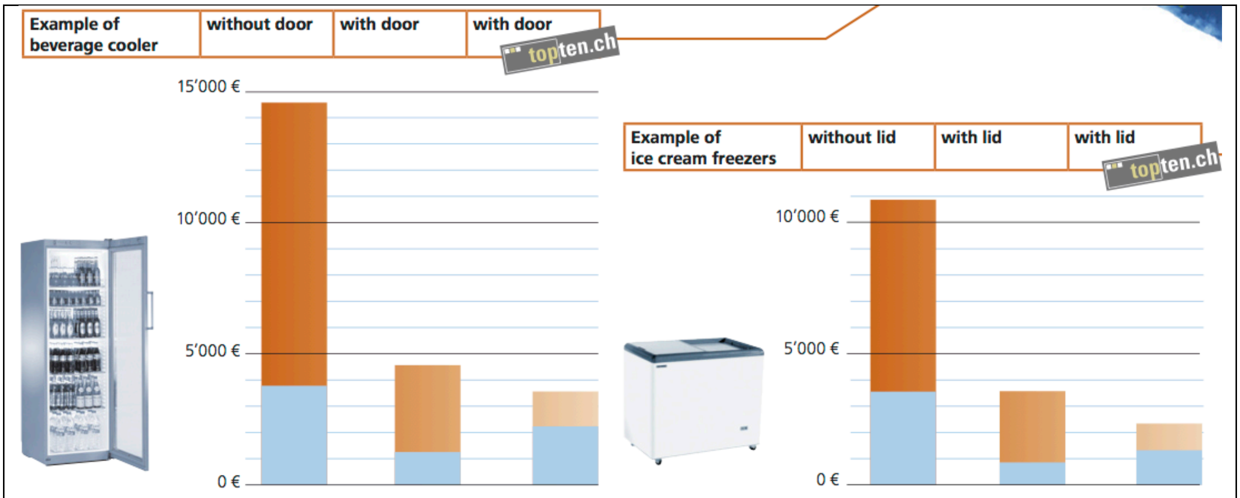


Figure 1: Energy consumption data from catalogues[3] for commercial and professional refrigerated cabinets (coloured lines = EU labelling classes for household refrigerating appliances)

The product comparison in Figure 2 is based on standardised data and shows closed cabinets use three times less energy than open cabinets. The best-available-technology closed products use up to eight times less energy.

[3] Current catalogues of two large suppliers in Switzerland (GKM and Kältering)



Example of beverage cooler	without door	with door	with door
Volume	324 litres	350 litres	346 litres
Energy	6'753 kWh/a	2'168 kWh/a	944 kWh/a
Electricity costs*	10'800 €	3'470 €	1'510 €
Purchase price	3'760 €	1'170 €	2'120 €
Total costs	14'560 €	4'640 €	3'630 €

* 8 years, 0.2 € /kWh

Example of ice cream freezers	without lid	with lid	with lid
Volume	151 litres	183 litres	190 litres
Energy	4'636 kWh/a	1'313 kWh/a	584 kWh/a
Electricity costs*	7'420 €	2'570 €	930 €
Purchase price	3'570 €	980 €	1'290 €
Total costs	10'990 €	3'550 €	2'220 €

* 8 years, 0.2 € /kWh

Figure 2: Product comparison with standardised data (source: ProCold brochure [3])

Figure 3 and Table 1 show the reference CO2eq emission savings used in the rebate programme in Switzerland [4]. CO2eq emissions are reduced by replacing ordinary refrigerants with green options, and by buying efficient products. Buying efficient products achieves CO2eq emission savings many times greater than replacing refrigerants (about by factor 4).

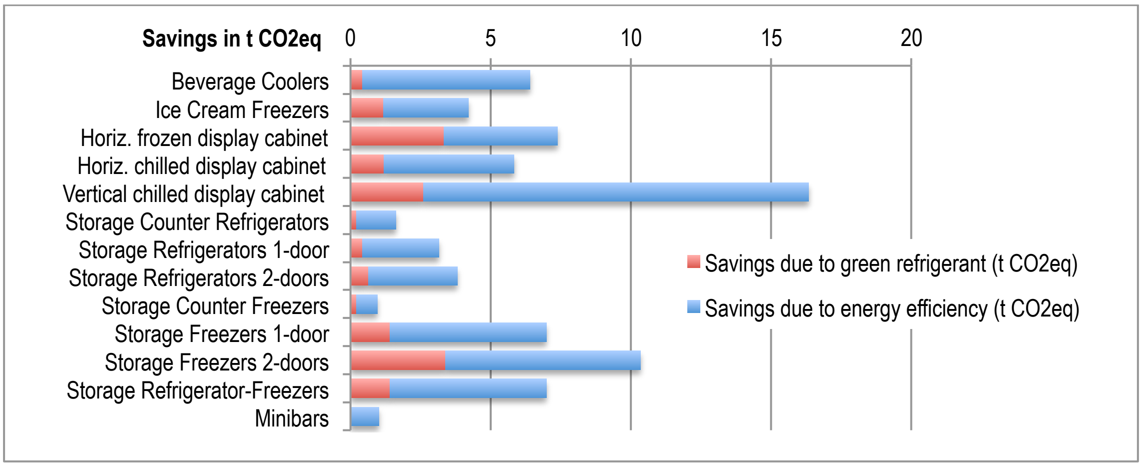


Figure 3: Greenhouse gas emissions saved with energy efficiency and green refrigerants

	Savings due to energy efficiency			Savings due to green refrigerant		Replaced refrigerant		
	kWh	t CO2eq		t CO2eq			kg	GWP
Beverage Coolers	14200	5.96	*93%*	0.43	*7%*	R134a	0.3	1430
Ice Cream Freezers	7192	3.02	*72%*	1.18	*28%*	R507	0.3	3920
Horiz. frozen display cabinet	9640	4.05	*55%*	3.33	*45%*	R507	0.85	3920
Horiz. chilled display cabinet	11024	4.63	*79%*	1.20	*21%*	R404A	0.3	3990
Vertical chilled display cabinet	32680	13.73	*84%*	2.59	*16%*	R404A	0.65	3990
Storage Counter Refrigerators	3352	1.41	*87%*	0.21	*13%*	R134a	0.15	1430
Storage Refrigerators 1-door	6472	2.72	*86%*	0.43	*14%*	R134a	0.3	1430
Storage Refrigerators 2-doors	7520	3.16	*83%*	0.64	*17%*	R134a	0.45	1430
Storage Counter Freezers	1760	0.74	*78%*	0.21	*22%*	R134a	0.15	1430
Storage Freezers 1-door	13288	5.58	*80%*	1.40	*20%*	R404A	0.35	3990
Storage Freezers 2-doors	16536	6.95	*67%*	3.39	*33%*	R404A	0.85	3990
Storage Refrigerator-Freezers	13288	5.58	*80%*	1.40	*20%*	R404A	0.35	3990
Minibars	2390	1.00	*100%*	0.00	*0%*	R717	0.1	0

Table 1: Greenhouse gas emissions saved with energy efficiency and green refrigerants[4]

Energy management systems

As part of the EU legislation process, new testing standards for beverage coolers (prEN 16902) and ice cream freezers (prEN 16901) have been developed. Energy-saving technologies like energy management systems (also called EMS or EMD) for beverage coolers and night covers for ice cream freezers[5] will be allowed and accounted for during testing. This will incentivise manufacturers to implement these technologies.

Energy management systems promise savings of 15-45%. Beverages do not need to be refrigerated at night; integrated EMS automatically switch beverage coolers into sleep-mode after opening hours. The European Commission Joint Research Centre (JRC), in its preparatory study update report on commercial refrigeration [15], says that EMS are the second most effective improvement option to achieve energy savings in beverage coolers and vending machines. The saving potential is estimated to be 26% on average and up to 45% in the best case. The most effective improvement option is using merchandisers with doors instead of open cabinets (yielding a reduction in energy costs by 40 – 50%). However, some beverage companies experienced that energy savings through EMS are lower (15% on average and up to 25% in the best case, based on 12 hours business-mode and 12 hours standby-mode per day, with a pull-down-phase of maximum 3 hours before business-mode). A field measurement in a canteen in Switzerland showed savings of 40% (Figure 4). The measurement was performed in December 2014. Energy consumption was reduced from 120 kWh per week to 71 kWh per week when the cooler is shut off over night and on Sunday (data was provided to Topten by the operator of the canteen anonymously).

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[4] Calculated with 0.42 kg CO2eq/kWh for EU electricity mix. Green refrigerants like R290 and R600a have GWP values of <4; thus their CO2eq emissions are very small compared to ordinary refrigerants and they were neglected in this calculation; Total refrigerant emission in EU was set to 100% assuming that there is no recycling (assumptions for Switzerland: about 26% with 1% annual emission during use phase of 8 years (10 years for minibars) and 80% recycling at end of life).

[5] Small ice cream freezers can be equipped with night covers that provide additional insulation for glass lids. Under the condition that they be fixed to the cabinet, night covers will be applied for the energy consumption test. The saving potential of night covers is yet unknown.

These predictable efficiency improvements should be considered when setting the stringency of the EU label classes.

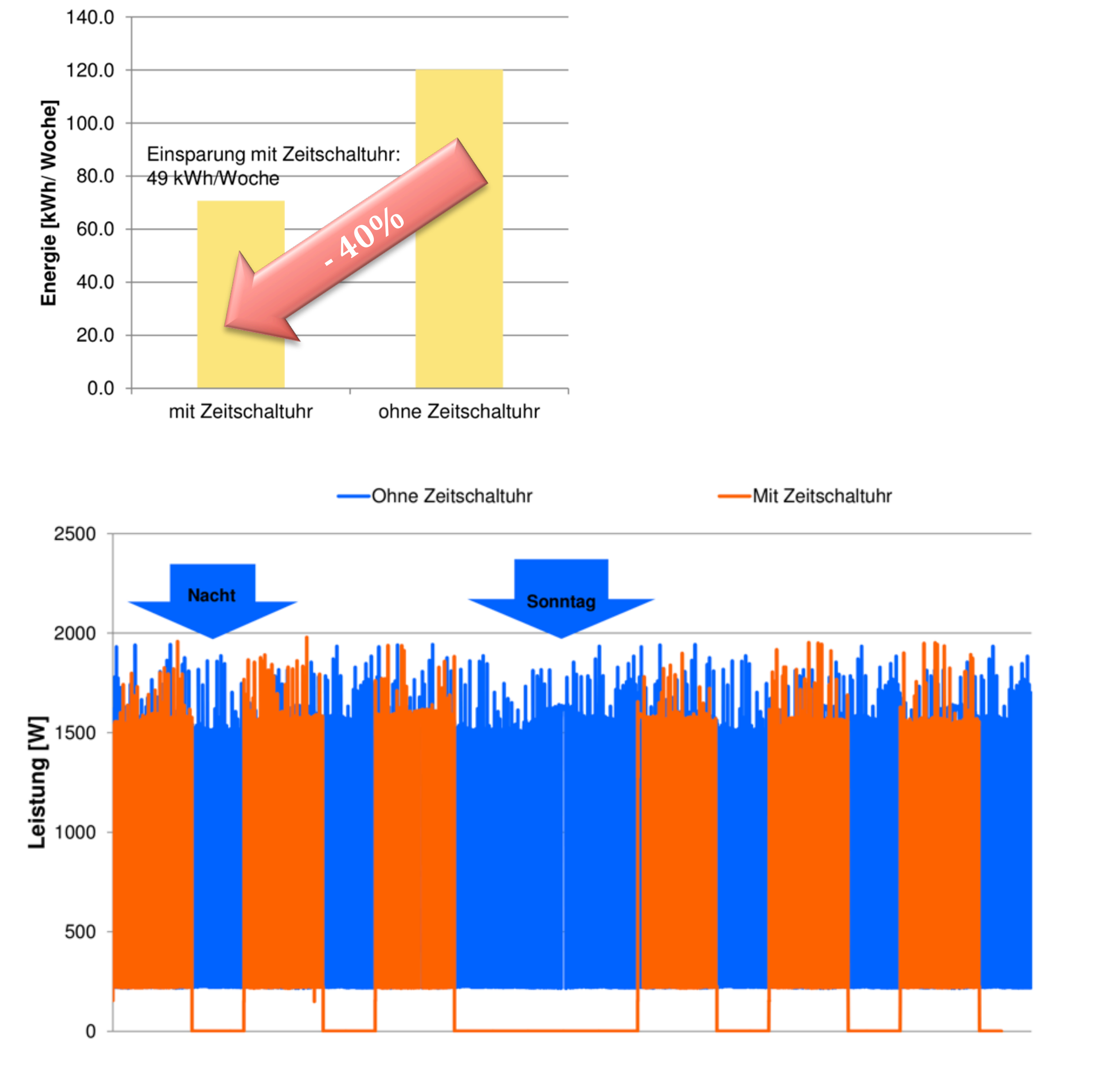


Figure 4: Field measurement of beverage cooler in a canteen shows 40% savings by shutting off at night and on Sundays (top: energy consumption in kWh/week, left with EMS, right without EMS; bottom: power in W, load profile over one week, orange with EMS, blue without EMS)

Barriers to energy efficiency gains

The biggest barrier for both manufacturers and buyers of commercial/professional refrigerated cabinets is that no standardised product information is available to compare the energy costs of different models. Energy consumption values are only found sporadically in catalogues and not suited for comparison because testing conditions are unknown. Figure 5 shows standardised energy consumption values compared to catalogue data for the same models. It becomes clear that energy consumption values declared in catalogues are typically lower than standardised energy consumption. An individual manufacturer has little incentive to declare standardised data because the values would be considerably higher. New product information requirements and EU energy labels are absolutely essential (recently adopted for professional refrigerated storage cabinets, still being developed for commercial refrigerated display cabinets, see later chapter).

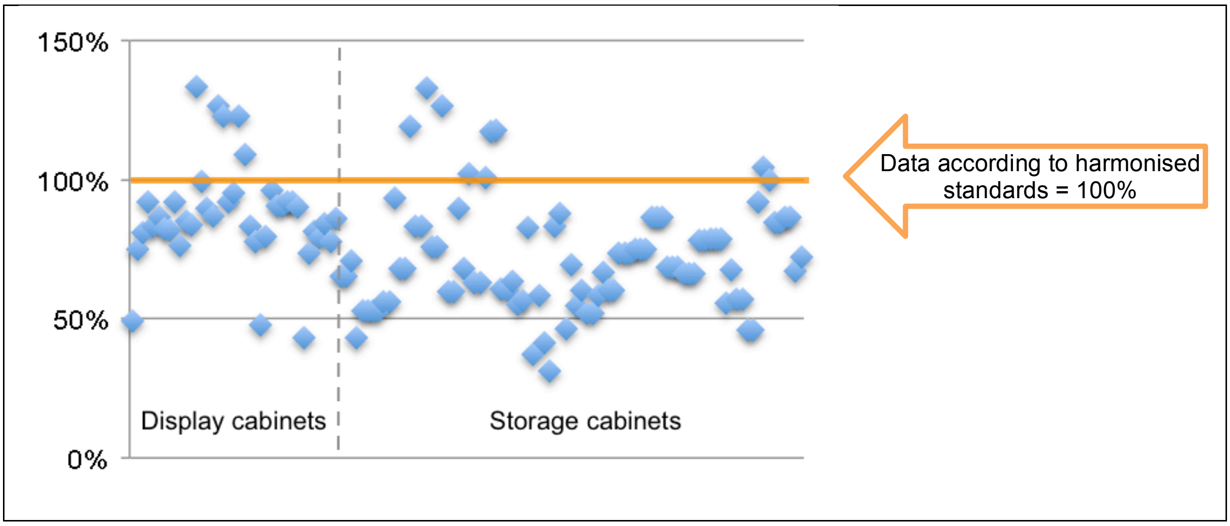


Figure 5: Energy consumption values found in catalogues in relation to data according to harmonised standards

The standardised energy consumption data was collected for the rebate programme in Switzerland. An overview of accepted testing standards, climate classes and temperature classes can be found on the programme website [4] [5].

Using cabinets with glass doors and lids instead of open cabinets would bring the greatest savings achieved by a single measure. The advantages are not only savings, but better hygiene and shopping climates. There are already retailers that implement a closed cabinet strategy, but for many others the fear of selling less is a barrier.

Barriers to introducing green refrigerants

Green refrigerants (with global warming potential, GWP, below 150) have been promoted for many years by numerous projects and campaigns[6]. These activities have successfully started to transform the market. Today there are commercial/professional products that use green refrigerants available for all cabinet types in all sizes. The only exception is large, 2.5 meter, open plug-in cabinets because their cooling capacity is too high[7]; they can use green refrigerants when fitted with glass doors and thus improve cooling capacity. So far the commercial/professional market has failed to follow the market for household refrigerating appliances in which green refrigerants have become common and are now mandatory due to the F-gas regulation [6]. Experiences with the rebate programme in Switzerland and interviews with Swiss industry experts lead to the conclusion that the main barrier for green refrigerants is not lack of awareness or training for professionals but instead the additional effort and expense that come along with the switch to green refrigerants. Professionals need to transport additional gear for maintenance (gas containers, manometer, specific tools) and invest in an expensive precision balance (R290 and R600a must be filled precisely to the gram). This extra effort and expense leads to a situation where many professionals do not recommend and offer products with green refrigerants to their customers.

With the new F-gas regulation [6], the EU decided to phase out climate-damaging refrigerants in commercial refrigerators and freezers by 2022 (see Table 2). The coming ban of climate-damaging

[6] To name four examples: 1) Greenpeace's Greenfreeze project initiated the use of climate-friendly refrigerants in household refrigerators and freezers [7], 2) Environmental Investigation Agency's annual report and retailer survey on natural refrigerant use [8], 3) Shecco supports industry in using green refrigerants with online technology platforms, market research, events etc. [9] 4) ProCool innovation competition in 2005 to support development and market introduction of products with green refrigerant (and energy efficiency) [10]

[7] The common green refrigerants for plug-in cabinets are isobutane (R600a) and propane (R290). Their use is restricted to 150g per cooling circuit because they are flammable. CO_2 is more commonly used for remote cabinets and is not flammable / restricted.

refrigerants is absolutely essential to overcome the barrier that currently impedes widespread uptake of green refrigerants in commercial/professional refrigerated cabinets.

10. Domestic refrigerators and freezers that contain HFCs with GWP of 150 or more		1 January 2015
11. Refrigerators and freezers for commercial use (hermetically sealed equipment)	that contain HFCs with GWP of 2 500 or more	1 January 2020
	that contain HFCs with GWP of 150 or more	1 January 2022

Table 2: Prohibitions for placing on the market in the f-gas regulation (excerpt) [6]

Rebate programme in Switzerland

Since September 2013, Swiss cities, cantons and utilities, with significant financial support from the Swiss Federal Office of Energy, operate a rebate programme for energy efficient commercial/ professional plug-in refrigerated cabinets with green refrigerants [4]. To overcome the described barriers and increase the market share of best-available-technology refrigerators and freezers, the programme pays back rebates of up to 25% of the purchase price for eligible models (Figure 6). With a budget of 3.7 million Euros, the aim is to subsidize about 5000 high-efficiency refrigerators and freezers until 2017. The projected electricity savings of the programme are 42 million kWh.

Rebates

Category	25% of the purchase price up to the following amount :
Beverage Coolers	570 EUR
Ice Cream Freezers	380 EUR
Display Chest Freezers	1150 EUR
Display Chest Refrigerators	950 EUR
Vertical Chilled Display Cabinets	2400 EUR
Storage Counter Refrigerators	380 EUR
Storage Refrigerators 1-door	760 EUR
Storage Refrigerators 2-doors	950 EUR
Storage Counter Freezers	190 EUR
Storage Freezers 1-door	1150 EUR
Storage Freezers 2-doors	1340 EUR
Storage Refrigerator-Freezers	1430 EUR
Minibars	280 EUR

Figure 6: Rebates for commercial/professional plug-in refrigerators and freezers with high efficiency and green refrigerants in Switzerland

Eligible models must be tested according to harmonised standards at defined climate and temperature classes [5]. The technical criteria for eligibility are 1) using green refrigerants (GWP <150) and 2) complying with minimum energy efficiency benchmarks whose stringency is dynamically strengthened as the market develops. The technical criteria are closely aligned with the respective EU legislation (e.g. calculation of energy efficiency indices) in order to achieve a harmonized methodology. All eligible products are published on the Topten.ch website with technical data and standard energy consumption. Thereby the rebate programme aims to create market transparency (at least for the top products on the market) and overcome one of the strongest barriers to efficiency development.

ProCold

In February 2015, a consortium of nine energy agencies, research institutes, a university and environmental organisations located in eight countries took up working to improve energy efficiency of commercial/professional plug-in refrigerators and freezers [3]. The three-year project called “ProCold” is funded by the European Commission’s Horizon 2020 programme.

Having recognised that lack of information and comparable product data is one of the strongest barriers for efficiency improvements, the project will empower Europe’s key stakeholders in distinguishing efficient products. One thousand players with leverage on the market will be personally contacted and provided with tools to stimulate both the supply and demand side. Tools and services of the project include:

- Lists of best-available-technology products are provided for national markets in Austria, Czech Republic, France, Germany, Italy, Portugal, Sweden and Switzerland (Figure 7).
- Logos to showcase best-available-technology models in catalogues or on the cabinets themselves.
- Procurement guidelines including texts to copy-paste into enquiries and calls for tender.
- Calculation tools for comparing costs between products and reporting energy and CO2 savings from green procurement.
- Key information is published in printed brochures, target-tailored to various stakeholder groups (Figure 7).
- The best model in various product categories will be recognised with an award, two years into the project.

The main stakeholder groups with leverage on the market include public authorities (policy making and public procurement), manufacturers and suppliers (manufacturing, researching and developing, marketing, branding and managing logistics of products), food and beverage industry (leasing or providing majority of ice cream freezers and beverage coolers), retailers and other direct users like gastronomy businesses, vending service providers, professional associations, organisations, media and events.

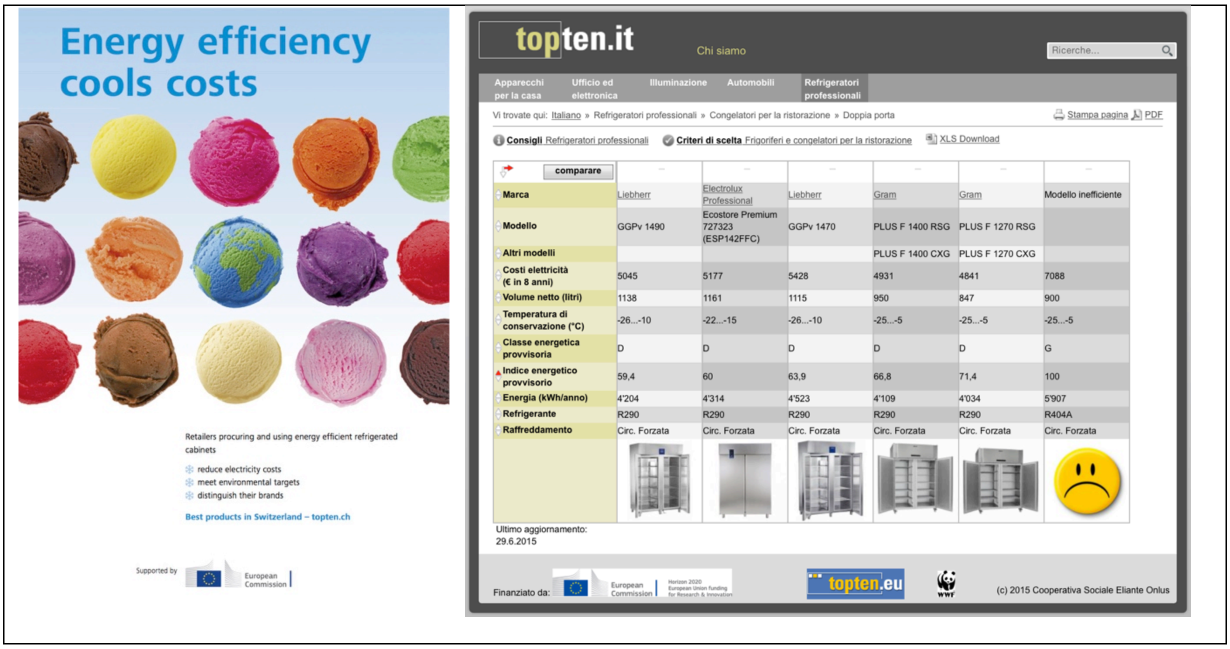


Figure 7: Left: ProCold brochure, right: list of best-available-technology products in Italy

EU legislation

New EU legislation for commercial/professional refrigeration products will, for the first time, create transparency regarding energy consumption and efficiency. This is 20 years after the EU introduced its energy label for household refrigerating appliances in 1995. There are three lots to consider:

- ENER Lot 13 (household refrigerating appliances)
- ENTR Lot 1 (professional storage refrigeration products)
- ENER Lot 12 (refrigerated commercial display cabinets)

EU legislation for professional storage products has just recently been adopted, with the first stage applying from July 2016 [11] [12]. A review of existing regulations covering household products is going on now and new regulations for commercial display products are being drafted [1] [13] [14] [15]. 2015 offers the opportunity to align the scopes so all important products are covered.

New regulations for professional storage refrigeration products (Lot 1)

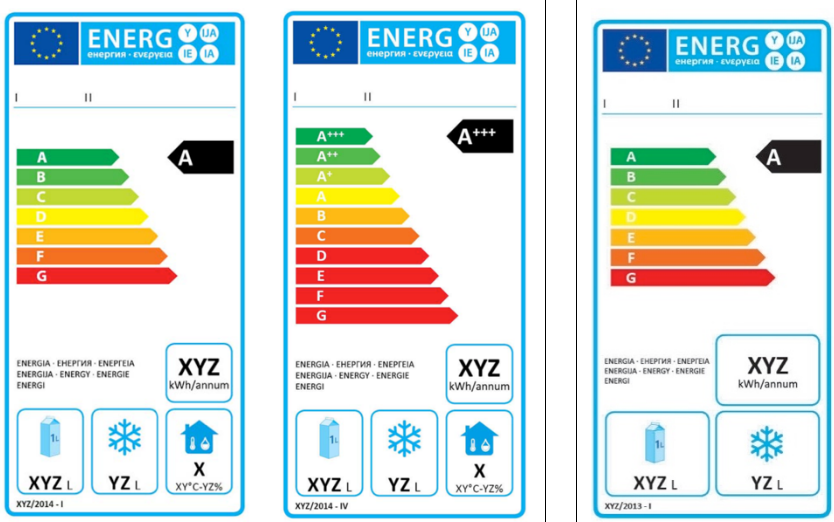
The ecodesign regulation covers four product groups: professional refrigerated storage cabinets, blast cabinets, condensing units and process chillers. The labelling regulation only concerns professional refrigerated storage cabinets.

The EU energy label (see Figure 8) will be mandatory from 1 July 2016. Manufacturers can already use the second label with plus classes. From 1 July 2019 all storage cabinets must be labelled with the second label.

Planned regulations for refrigerated commercial display cabinets (Lot 12)

The draft ecodesign and labelling regulations cover five product groups: supermarket segment refrigerated display cabinets, beverage coolers, small ice-cream freezers, soft scoop ice-cream cabinets and refrigerated vending machines. The current draft of the EU energy label for display cabinets adheres to the traditional A-G scale and does not include plus classes (see Figure 8).

Storage cabinets: Display cabinets (draft):



: 1st July 2016 1st July 2019 1st January 2017

Figure 8: EU energy labels for storage cabinets and display cabinets

Gaps in the scope of the legislation

Considering how crucial product information is for efficiency development, it is important that the new EU legislation supports standardised declarations of energy consumption for all products. Good examples are storage refrigerator-freezers and blast cabinets: even though it was not possible to introduce minimum energy efficiency requirements in the recently adopted EU regulation, mandatory declaration of energy consumption has been included. This will provide a basis for voluntary actions (i.e. in the frameworks of the rebate programme and ProCold project) and ensure that the next revision of the legislation will happen on a well-informed basis.

Product types currently excluded from legislation that would ensure standardised declaration of energy consumption:

- Storage chest freezers
- Storage static-air cabinets
- Display vertical static-air cabinets
- Commercial wine storage appliances
- Commercial minibars

It is important they are included in coming regulations during the ongoing legislation process for household and commercial products. Their exemption would lead to awkward gaps in the declaration. Products that are technically and functionally the same will be arbitrarily covered by legislation or not, depending if they are marketed for domestic or commercial/professional use.

Green refrigerants could be showcased on the label

A simple and effective measure could be to showcase cabinets using green refrigerants (with global warming potential below 150) with an icon and/or note on the label (Figure 9). This would ease market transition towards the ban high-GWP refrigerants in 2022.

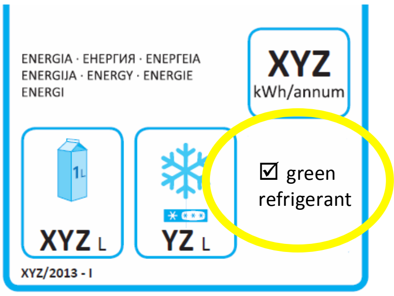


Figure 9: The labels could showcase cabinets using refrigerants with global warming potential below 150

Conclusions

That energy consumption is declared in a standardised way is absolutely crucial for the market to develop towards efficiency. New EU legislation will for the first time create market transparency for commercial and professional refrigeration products. It is important that the scopes of the three legislation lots are well aligned. Currently there are gaps in the scopes that should be addressed during the ongoing draft and revision process.

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Smart Homes

How much electricity can we save by using direct current circuits in homes? Understanding the potential for electricity savings and assessing feasibility of a transition towards DC powered buildings

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Abstract

Advances in semiconductor power electronics and growing direct current loads in buildings have lead researchers to reconsider whether buildings should be wired with DC circuits to reduce power conversions and facilitate a transition to efficient DC appliances. The feasibility, energy savings, and economics of such systems have been assessed and proven in data centers and commercial buildings, but the outcomes are still uncertain for the residential sector.

In this work, we assess the technical and economic feasibility of DC circuits using data for 120 homes in Austin, Texas to understand the effect of highly variable demand profiles on DC-powered residences, using appliance-level use and solar generation data, and performing a Monte Carlo simulation to quantify costs and benefits.

Results show energy savings between 10-21% when solar PV is distributed to all home appliances. When battery storage for excess solar energy is considered, these savings increase to 13-23%. At present DC equipment prices, converting all equipment to DC causes levelized annual costs of electricity to homeowners to roughly double. However, by converting only homes' air conditioning condensing units to DC, the costs of direct-DC are greatly reduced and home energy savings of 7-17% are generated.

In addition to quantifying savings, we find major nontechnical barriers to implementing direct-DC in homes. These include a lack of standards for such systems, a relatively small market for DC appliances and components, utility programs designed for AC power, and a workforce unfamiliar with DC. Experience with DC is growing in other sectors, and with time this will be transitioned to a broader audience of engineers, electricians, and building inspectors to ensure that not only are the systems themselves safe, but that the image of direct current circuits becomes less foreign over time. Direct current may very well have a place in the residential sector, and research and development should continue to explore other potential benefits that might make a stronger case for a more widespread transition to what now appears a promising technology.

Introduction

Advances in semiconductor-based power electronics have made efficient direct current voltage transformation possible, leading scientists and engineers to reconsider the benefits of this previously niche technology. The resulting research has led to the adoption of direct current power in high voltage transmission, data centers, and commercial lighting applications, among others (Ton et al., 2008) (Thomas et al., 2012) (Schavemaker et al., 2008). As additional benefits have been realized, a discussion has emerged as to whether more buildings should be wired with DC circuits in addition to – or in place of – AC (Savage et al., 2010) (Garbesi et al., 2011) (Vossos et al., 2014) (Paajanen et al., 2009) (George, 2006) (Pratt et al., 2007). Around 50% of the energy presently used in buildings is either consumed as DC in electronic loads or passes through a transient DC state as a means of motor control, resulting in significant losses when grid distributed AC is rectified using inefficient power supplies (Savage et al., 2010). When a source of DC generated electricity such as a solar PV array is available, a dedicated DC circuit would eliminate the usual losses that occur both in the inversion from generated DC to grid AC, as well as the rectification back to DC at the end load.

Several trends point to the residential sector as a prime candidate for a transition to DC. Residential buildings currently account for about 15% of all energy consumption in the US (EIA, 2013) and 21% of all greenhouse gas emissions, 71% of which are a result of electricity use in homes (EPA, 2013). Making up approximately 35% of that energy consumption are appliances, electronics, and lighting, which can all operate on DC (EIA, 2009). Lastly, the federal solar investment tax credit, utility net energy metering programs, and renewable portfolio standards have together resulted in consistent growth in residential PV installations that is not expected to slow (SEIA, 2014). Together these factors have made DC microgrids the topic of substantial research which has detailed several aspects of these systems.

Thomas, Azevedo and Morgan (Thomas et al., 2012) analyzed direct-DC LED lighting in a 48,000 ft2 office building and estimated a reduction in the levelized annual cost of an LED lighting system of 2-21% compared to a grid-connected AC system. Another study by Savage at al. looked at centralizing the conversion from grid AC to DC from distributed “wall warts” to a central home-level rectifier. This study estimated 25% energy savings across the US residential sector (Savage et al., 2010). Most recently, under a Department of Energy (DOE) initiative investigating DC power in residential and small commercial markets, Garbesi et al. (Garbesi et al., 2011) catalogued and characterized a range of existing and future appliances that are compatible with DC power. In a follow-up report (Vossos et al., 2014), the same group estimated the energy savings associated with a direct-DC home with PV using simulated home loads and solar generation profiles in 14 cities across the US. This study estimated a 5% electric savings in direct-DC homes without storage for generated solar energy and 14% savings with storage. In the summary report filed for this initiative, the authors identify four areas for continuing research in direct-DC power systems: developing direct-DC products, developing standards and test procedures, building demonstration projects, and improving techniques for modeling energy savings.

This study takes the recommendation of the DOE report and models DC residential systems using a unique dataset with one-minute interval data measured at the home-, circuit-, and appliance level in single-family homes in Austin, Texas provided by the Pecan Street Research Institute (Pecan Street, 2014). The use of monitored data allows us to understand the effect of highly variable energy consumption and solar generation patterns on DC-powered residences not available in the modeled data. The method established for this analysis uses Monte Carlo simulation to account for uncertainty in the inputs to the DOE model. Included in this simulation, we provide a first analysis of the economic feasibility of a DC-powered home using levelized annual cost of electricity to the customer and the cost-effectiveness for avoided CO2 emissions. Additionally, we investigate voltage standards, utility billing and incentive programs, appliance and component markets, and building codes to determine their effects on increased use of DC power in the residential sector.

Data and Methods

Appliance-Level Energy Use Data

Appliance-level and home-level energy consumption data, as well as solar PV generation data used in the analysis were obtained from Pecan Street Research Institute’s Dataport. Pecan Street Inc. is a 501(c)(3) not-for-profit corporation and research institute headquartered at The University of Texas at Austin. Volunteer homeowners in and around Austin elect to join the study and work with Pecan Street to decide which circuits and appliances to monitor. The resulting dataset includes records for approximately 693 homes, with data available for up to 28 circuits per home at one-minute intervals. The first homes in this sample begin reporting data in January 2012, and installations are ongoing. Average electricity consumption for households in Pecan Street’s sample is approximately 85% of the local utility’s average residential customer (Austin Energy, 2014). These households are therefore likely to provide a reasonable approximation of household electricity consumption around Austin.

For final whole-home simulations in our analysis, we select homes which had total electricity use and at least air conditioner condensing unit use, central air supply fan use, and refrigerator use monitored for over one year with less than one week of missing data. In Table 1 we provide information on the number of houses for which we have different levels of information. From the original 693 homes, 279 have over one year of whole-home use data. Of these only 120 had monitored the appliances listed above. Of these remaining 120 homes, 40 had data for an electric vehicle charger and 45 had data for a solar PV array. For houses without PV, we use a proxy monitored PV generation profile taken from a typical system in the sample.

Table 1. Data validation criteria for final simulations.

Validation criteria	Qty. of homes
Total homes in dataset	693
Homes with ≥1 year of whole-home use monitored	279[a]
+ Whole-home, AC condensing unit, central air supply fan, and refrigerator use monitored	120[a]
+ Electric vehicle charger monitored	40[a]

[a] Counts include only datasets with less than one week of data missing

Appliance Class Allocations

To estimate energy, emissions, and cost savings associated with a transition to DC circuits, monitored appliance data for each home was separated into five classes based on power supply and load type. In simulating energy savings from a conversion to DC, appliances in each class will see the same change in efficiency.

The difference between the sum of monitored loads in each home and the home's total metered use was assigned to 'Other Loads' which we attribute to electronics, lighting, kitchen appliances, and plug loads. These devices were not consistently monitored but are known to contribute substantially to total home load (EIA, 2009). Table 2 summarizes these allocations.

Table 2. Appliance class allocation.

Refrigeration Loads	AC Motor Loads	Electric Vehicle Loads	Resistance Heating Loads	Other Loads
HVAC condensing unit, freezer, refrigerator, wine cooler	Kitchen disposal, clothes washer, central air supply fan, gas clothes dryer, vent hood fan	Electric vehicle charging	Oven, range, electric clothes dryer[a], dishwasher[b], electric water heater	All electronics, CFL and LED lighting, kitchen appliances, miscellaneous plug loads

[a] Electric clothes dryer energy consumption is comprised of resistance heating and AC motor load. By comparing Pecan Street data for gas dryers and electric dryers, we assign 20% of total energy consumption to AC motor loads and 80% to resistance heating.

[b] Dishwasher energy consumption is similarly comprised of resistance heating and AC motor load. We assign 30% of total energy consumption to AC Motor Loads and 70% to Resistance Heating based on [9].

The annual energy consumption of each appliance class was calculated for the sample homes. The same allocation was applied to the most recent RECS data and was plotted for comparison in Figure 1. The data generally show similar proportions of energy use for the major appliance classes.

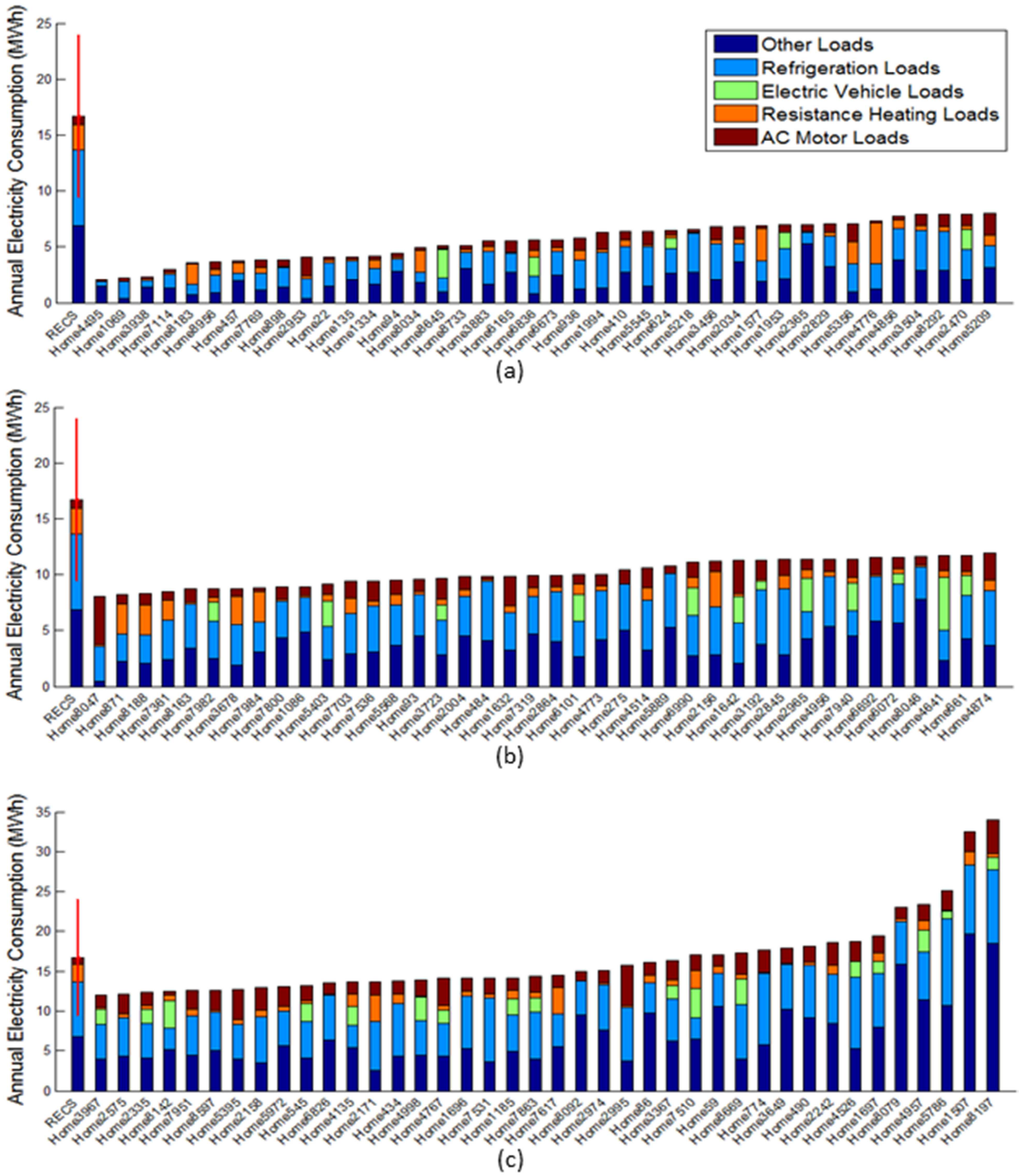

Figure 1. Annual energy consumption by appliance class. The first bar in each figure shows the mean electricity consumption by appliance class reported in RECS for single family homes in Texas with central air. Error bars show plus or minus one standard deviation from this mean. (a)-(c) show energy use breakdowns by appliance class for Pecan Street homes included in final simulations ordered by annual energy consumption and separated to show one third of total homes in each graph. Data: Pecan Street [21], RECS [8], and [9]

DC Compatible Appliances

Every major appliance in a modern home could be replaced by a more efficient device that can operate on DC (Garbesi et al., 2011). Most of these devices are currently intended for off-grid applications, where high equivalent electricity prices incentivize high efficiencies. While prices for such equipment are now prohibitively expensive for widespread residential use, their fundamental designs and capacities are suitable for the residential sector (Garbesi et al., 2011). Garbesi at al. catalogued the manufacturers of many of these devices in (Garbesi et al., 2011). For example, the motors currently found in home appliances are primarily a mix of AC induction motors for larger loads and universal motors for smaller loads (Paajanen et al., 2009). Brushless DC permanent magnet (BLDC) motors are inherently more efficient than both types of motors, with savings estimated at 5-15% for constant speed applications (Garbesi et al., 2011). In variable speed configurations, BLDC motors operate even more efficiently and generate substantial savings when compared to AC motors.

In air conditioner condensing unit applications, existing variable speed refrigerant compressors driven by BLDC motors achieve cooling efficiencies nearly twice the minimum requirement for Energy Star certification (DCAirco, 2014) (Energy Star, 2014). By comparing the energy efficiency ratios (EERs) of these units to those recorded in Pecan Street's energy audit records, we establish an efficiency improvement for converting a traditional condensing unit to a BLDC equivalent. Because the same vapor-compression cycle is used in refrigerators, freezers, and wine coolers, we apply the same efficiency improvement to the entire refrigeration load appliance class.

Resistance heating elements can be powered by AC or DC. While alternatives for resistance heating exist that utilize heat pumps or induction heating, we assume no change in resistance heating energy consumption with a transition to DC.

Of the 120 homes included in our final simulations, 40 have plug-in electric vehicles (PEVs) with home chargers. EV chargers operate internally on DC, requiring rectification of the existing AC supply and a subsequent DC-DC voltage transformation. In a DC home, this power supply would be simplified to a sole DC-DC converter, eliminating rectification losses.

Remaining loads in the monitored data are assumed to be comprised of lighting and consumer electronics. All modern consumer electronics operate internally on DC and therefore require variants of switched-mode power supplies to generate their necessary DC voltage. Similar to EV charging circuits, these consist of a rectification stage typically followed by a DC-DC voltage transformation. A DC circuit would eliminate the losses associated with the initial rectification.

Based on Pecan Street survey results, compact fluorescent lamps (CFLs) are the most common primary lighting technology in the sampled homes. One DC alternative is to use light emitting diodes (LEDs), which are the chosen technology for direct-DC lighting microgrids in the commercial sector. We use DOE lighting efficacy values to determine the efficiency improvement associated with converting the existing homes' lighting to LED.

DC Home Configurations

For homes in our sample, we perform simulations for the scenarios shown in Table 3. Figure 2 shows schematic diagrams of these configurations.

Table 3. Summary of simulated scenarios

DC Appliance(s)	Battery Storage
All	No
All	Yes
Lighting only	No
Lighting only	Yes
Air conditioner condensing unit only	No
Air conditioner condensing unit only	Yes
PEV charging station only	No
PEV charging station only	Yes
Refrigerator only	No
Refrigerator only	Yes

Figure 2(a) shows a home with no solar array and traditional AC circuits. Figure 2(b) shows a home with a net-metered PV array connected to traditional AC circuits. These two home configurations serve as baselines for the analysis as their exact consumption and solar generation were monitored.

The system shown in Figure 2(c) is similar to that analyzed by Vossos et al. in (Vossos et al., 2014). This configuration features a solar PV connected DC circuit supplying all home loads with and without battery storage (depicted by dashed line). When solar power is available, either as direct feed-in from the array or as stored energy, savings are generated as the initial inversion from generated DC to AC for distribution and the rectification back to DC required for electronic and EV charging loads are eliminated. When solar power is not available or is insufficient in meeting the home's load, grid power is rectified in a central home bi-directional inverter to meet the balance. When solar power exceeds the home's load, this device acts as a traditional inverter and allows excess power to be sold to the grid under existing net metering agreements (Vossos et al., 2014) (Austin Energy, 2014). In both the case of net energy exporting and purchasing, no energy or cost savings are generated on the exported or purchased energy, as this configuration is equivalent to the base PV scenario. In addition to generating savings by eliminating conversion stages, the simulations for these configurations assume the transition to more efficient DC compatible loads discussed above.

The remaining systems shown in Figure 2 simulate direct-DC circuits supplying individual appliances or appliance classes. Given that the transition to DC circuits in the commercial market began with standalone lighting circuits, we simulate four appliances with substantial contributions to home energy consumption and energy savings potential to determine if a similar opportunity exists in homes. This strategy may be the most cost-effective if a large proportion of potential whole home energy savings from DC conversion can be generated by a single appliance.

Each of these four appliances was simulated with and without storage for each house individually. Lighting data was not consistently available, as lighting and plug loads are often on common circuits. Lighting energy allocations are therefore based on the DOE's Residential Lighting Usage Estimate Tool, a companion to a report released in 2012 (Res. Ltg Tool, 2014). By comparing the annual lighting energy consumption values in this tool to the unaccounted "Other Use" in the RECS data, we estimate 25% of "Other Use" is due to lighting.

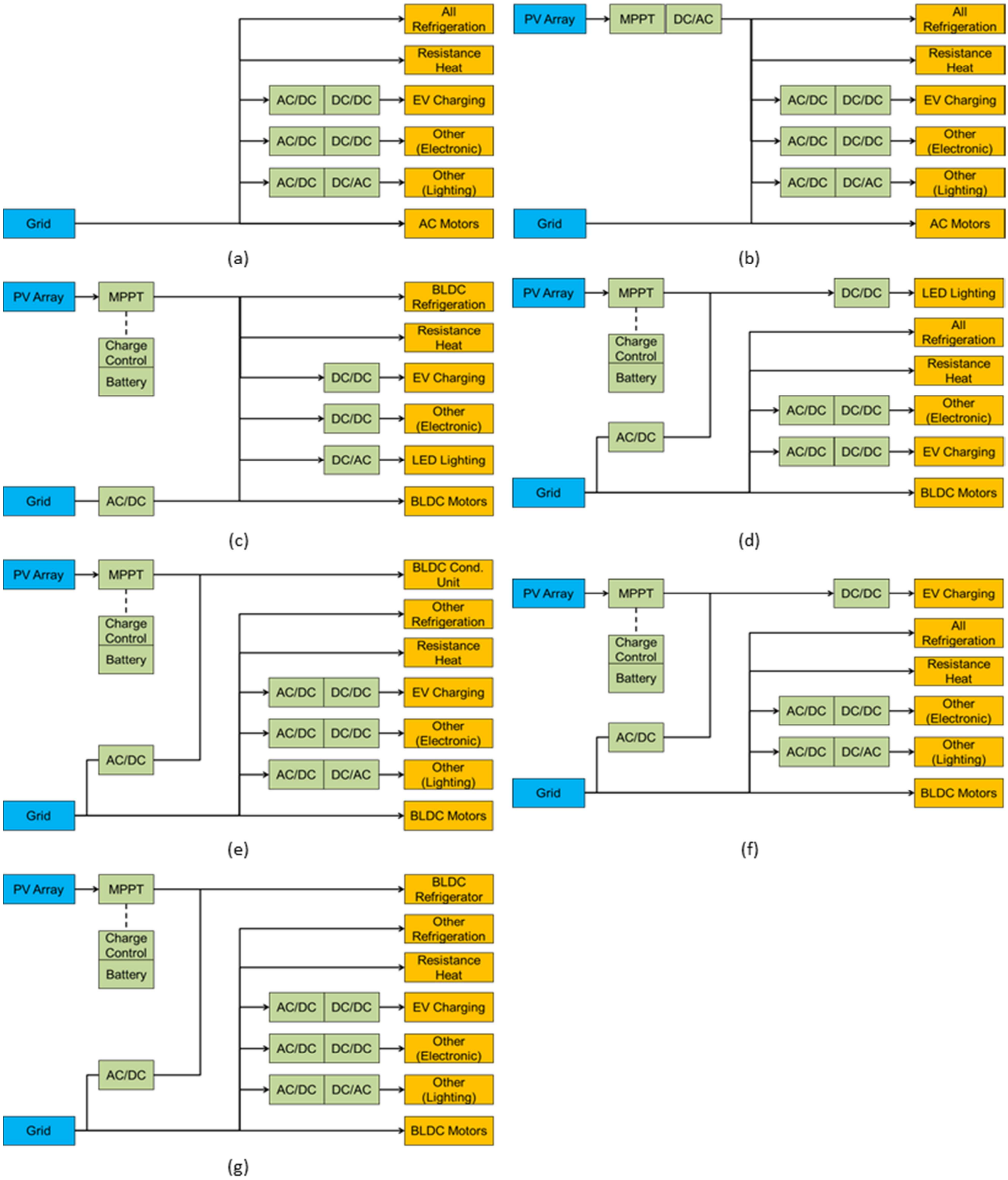

Figure 2. Schematic diagrams of simulated home configurations: (a) traditional home with AC distribution, without PV (b) traditional home with AC distribution and net-metered solar PV (c) home with DC distribution to all loads and net-metered PV with grid-rectified backup (d) home with DC distribution to a lighting circuit and net-metered PV with grid-rectified backup (e) home with DC distribution to a condensing unit and net-metered PV with grid-rectified backup (f) home with DC distribution to a PEV charger and net-metered PV with grid-rectified backup (g) home with DC distribution to a refrigerator and net-metered PV with grid-rectified backup.

Modeling Operations

Each of the ten scenarios depicted in Figure 2(c) through Figure 2(g) (five scenarios with and without storage) simulates 1,000 iterations of every home in the final sample. Each simulation selects a unique combination of the parameters listed in

Table **4**. These 1,000 combinations of parameters are then applied to each home in the simulation. This results in 1,000 annual energy consumption profiles, bills, and levelized annual costs (LACs) for each home. Each simulated scenario uses all (120) homes with complete data, except for EV simulations. Only (40) homes in the sample had monitored data available for electric vehicles, so these simulations use this smaller sample of homes. Note all simulations are applied to 15-minute interval profiles for the most recent year of data available for each home, resulting in 35,040 readings for 1 year.

For each appliance class j that is simulated being served by DC, a new load profile is calculated as a function of existing and proposed power supply and end use efficiencies as shown.

$$\mathrm{NewDCLoad_j}\Big|_{t=1}^{35,040} = \frac{\mathrm{MonitoredLoad_j} \cdot \eta_{\mathrm{existing,powersupply}} \cdot \eta_{\mathrm{existing,enduse}}}{\eta_{\mathrm{new,powersupply}} \cdot \eta_{\mathrm{new,enduse}}} \tag{1}$$

Each home's DC solar generation profile is calculated as eliminating the losses associated with an inverter.

$$\mathrm{NewPV}|_{t=1}^{35,040} = \frac{\mathrm{MonitoredGeneration}}{\eta_{\mathrm{existing,inverter}}} \tag{2}$$

The savings associated with direct-DC distribution of solar power is determined by the amount of the home's load that can be met by this new solar generation. Any load that exceeds the output of the solar array must be met by rectifying grid power to meet the home's DC load, which reintroduces a conversion loss. Alternatively, any solar array output which cannot be consumed or stored must be inverted and sold to the grid, again reintroducing a conversion loss. We determine new whole-home consumption as follows.

$$\mathrm{MetbyPV}|_{t=1}^{35,040} = \min(\mathrm{NewPV}, \textstyle\sum \mathrm{NewDCLoads}) \tag{3}$$

$$\mathrm{GridRectified}|_{t=1}^{35,040} = \frac{(\sum \mathrm{NewDCLoads}) - \mathrm{MetbyPV}}{\eta_{\mathrm{new,rectifier}}} \tag{4}$$

$$\mathrm{NewHomeLoad}|_{t=1}^{35,040} = \mathrm{MetbyPV} + \mathrm{GridRectified} \tag{5}$$

With annual electric consumption calculated, LAC is used to evaluate the economic feasibility of each proposed scenario. Only new home applications are considered, as an AC-to-DC retrofit would have a large capital cost – on the order of $6,000 to $10,000 – that would not soon be recovered by even the largest energy cost savings realized here [19]. LAC takes into account varying lifetimes of system components as well as the time value of money. Capital costs for each major system component k include equipment and installation costs, as well as applicable Austin Energy rebates. Electric costs and solar energy credits are calculated using Austin Energy's tiered rate structure for residential customers. Details of these billing rates, solar crediting rates, and solar PV rebates can be found in Appendix F. CRF, the capital recovery factor, is used to annualize a capital expenditure over the lifetime of n equipment capital investments with discount rate i.

$$\mathrm{LAC_l} = \mathrm{NetAnnualElectricCost_l} + \textstyle\sum_{m=1}^{n}[\mathrm{AddedCapitalCost_m} \times \mathrm{CRF_m}] \tag{6}$$

$$\mathrm{CRF_m} = \frac{\mathrm{i}}{1-(1+\mathrm{i})^{-\mathrm{lifetime_l}}} \tag{7}$$

To account for the uncertainty in prices and efficiencies of the proposed systems, ranges of possible values were established for all uncertain engineering and economic parameters, shown in

Table **4**. Monte Carlo simulations draw from uniform distributions between these ranges to calculate energy savings, electric cost savings, and LACs. Correlation between variables is not considered here as data for determining dependence (e.g. between component efficiencies, lifetimes, and costs) was not readily available.

Table 4. Parameters and ranges used in Monte Carlo simulations.

	Min	Max	Unit	Source
Engineering Parameters				
Existing or New Inverter Efficiency	0.87	0.94		[14]
Existing or New Rectifier Efficiency	0.93	0.97		[21]
DC-DC Converter Efficiency	0.80	0.90		[28]
Battery Charge Efficiency	0.95	0.95		[18]
Battery Discharge Efficiency	0.95	0.95		[18]
Pecan Street Condenser Efficiency	7.6	13.5	EER	[21]
DC Condenser Efficiency	16	22	EER	[3]
BLDC Motor Efficiency Gain	0.05	0.15		[13]
CFL to LED Efficiency Gain	0.07	0.28		[6]
Circuit Breakers per Home	20	20		
Battery Storage Capacity	2	2	hours	[5]
Battery Minimum Charge	0.2	0.2		[30]
Economic Parameters				
PV Module Cost	750	910	\$/kW-AC installed	[24]
PV Balance of System Cost	3,440	4,200	\$/kW-AC installed	[24]
Inverter Cost	250	310	\$/kW-AC installed	[24]
Rectifier Cost	250	310	\$/kW-AC installed	
Bidirectional Inverter Cost	500	620	\$/kW-AC installed	
AC Condensing Unit Cost	700	1,200	\$/kW-AC installed	[16]
AC Supply Fan Cost	1,800	4,300	\$/kW-AC installed	[16]
AC Refrigerator Cost	900	2,200	\$/unit	[16]
AC Circuit Breaker Cost	40	50	\$/unit	[15]
DC Condensing Unit Cost	2,400	2,400	\$/kW-DC installed	[2]
DC Supply Fan Cost	3,400	4,700	\$/kW-DC installed	[16]
DC Refrigerator Cost	1,700	2,700	\$/unit	[2]
DC Circuit Breaker Cost	130	150	\$/unit	[15]
Battery Cost	130	310	\$/kWh storage	[15]
Discount Rate	0.05	0.10		
Austin Energy Parameters				
Austin Energy Solar Rebate	2,990	2,990	\$/kW-AC installed	[1]
Electric Rate (see Appendix F)	Varies	Varies	\$/kWh consumed	[1]
Solar Credit Rate	0.107	0.107	\$/kWh generated	[1]
Lifetime Parameters				
PV Panel Lifetime	20	20	Years	[17]
Balance of System Lifetime	20	20	Years	
Inverter Lifetime	10	10	Years	[28]
Rectifier Lifetime	10	10	Years	
Bidirectional Inverter Lifetime	10	10	Years	
Battery Lifetime	10	10	Years	[28]
AC Appliance Lifetime	10	10	Years	
DC Appliance Lifetime	10	10	Years	
Circuit Breaker Life	20	20	Years	[28]
Simulation Parameter				
Number of runs	1,000	1,000		
Environmental Parameter				
ERCOT grid emission factor	1,218	1,218	$lbCO_2/MWh$	[12]

Modeling Assumptions

In final simulations, we make several assumptions about the efficiency, operation, and costs of the simulated systems.

First, we assume similar degradation of efficiencies of AC-DC and DC-DC power supplies under part load conditions. Because we use monitored load data, the lower efficiencies typically seen at part load in today's power electronics are included in the monitored load profiles. Therefore, in applying the new power supply efficiencies associated with direct-DC relative to the existing efficiencies as shown in Equation 1, we effectively account for degradation in the proposed systems' efficiencies at part load. We also assume that the high efficiencies currently seen in niche DC appliances will be maintained in the first generation of residential products. Many of these products are already available for off-grid monitoring stations, military installations, and mobile applications such as boats and RVs, among others. In these scenarios, high equivalent electricity costs put a premium on energy efficiency. We assume that in bringing these products to a larger residential market, these high efficiencies would be maintained.

Lastly, we assume line losses in the home are comparable to those in a traditional AC home. There is presently no consensus on a future residential DC voltage standard between key stakeholders such as the IEEE, EMerge Alliance, and SAE. This standard will have implications for wiring and component specifications to ensure safe, efficient, and cost-effective power delivery in residential settings. For this modeling, we assume no significant changes in line losses, wiring costs, or components. This would be the case if the future DC voltage standard is at or near the existing 120 VAC standard.

Results

Direct-DC Energy Savings

Figure 3 shows the resulting energy savings of the ten simulated scenarios as a percentage of each home's baseline energy consumption. Average savings in whole-home DC simulations are between 10-21% (mean ±1 standard deviation) and increase to 13-23% with storage.

The majority of these savings are attributed to DC condensing units, which alone generate around 12% mean savings that increase to around 13% with storage. These savings are a result of the large fraction of home energy consumption that these devices contribute, the efficiency gains associated with BLDC units, and load profiles that align well with solar output.

Lighting loads and EV charging loads generate little energy savings when converted to DC due to their relatively small contribution to whole-home load and the modest savings associated with a conversion to DC. Additionally, these appliances typically have load profiles that do not align well with solar generation and therefore would not be expected to be good candidates for direct-DC.

The relatively flat load profiles, substantial energy consumption, and the same efficiency improvements seen in air conditioning condensing units result in whole-home savings of around 1-6% when refrigerators are converted to DC.

For results shown in terms of annual kWh saved per home, see Figure 9 in Appendix G. These show median savings of around 1,500 kWh/yr and 1,700 kWh/yr for whole-home DC simulations without and with storage, respectively. As in Figure 3, the majority of these savings come from air conditioning condensing units, which alone generate median savings of around 1,100 kWh/yr and 1,200 kWh/yr without and with storage, respectively.

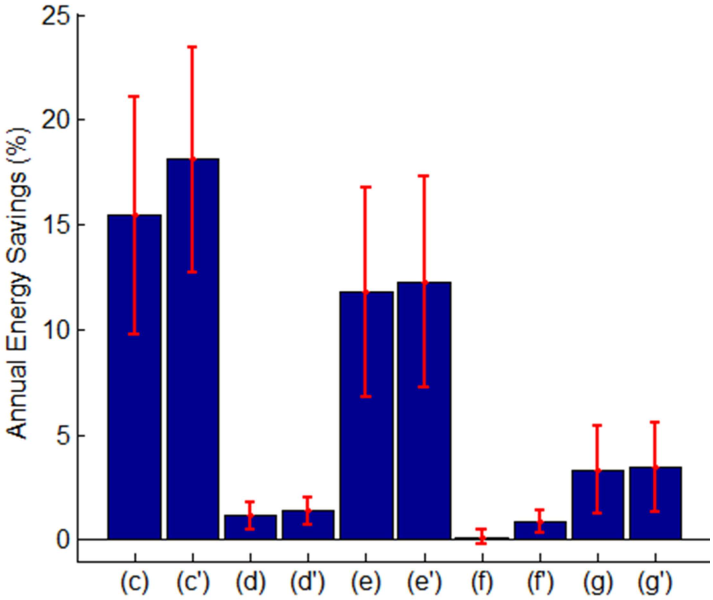

Figure 3. Annual energy savings for simulated direct-DC systems. Savings are reported as a percentage of baseline energy consumption of traditional AC homes. Simulation results correspond to the systems shown in Figure 2(c) through Figure 2(g). Primes indicate results with battery storage for solar generated energy. Error bars show plus or minus one standard deviation from the mean.

Direct-DC Energy Cost Savings – Present DC Equipment Market
In this section we consider the monetary costs and benefits associated with outfitting a new home with DC circuits, appliances, and devices at existing equipment prices. Using the energy savings results presented in Section 3.1, we calculate new electricity bills and annual solar credits for every home and every simulation using Austin Energy's billing and solar crediting rate structures.
Assuming a 120VDC standard means the installation and physical wiring in a DC home would be nearly identical to that in a traditional 120VAC home, incurring no extra wiring cost. Traditional residential-size circuit breakers, switches, and wall outlets are readily available and are often compatible with DC, but are rated to operate at a lower voltage (Grainger, 2014). Of these components, only the cost of breakers is significant – on the order of $1,000 per home – so we account for only this added component cost in each home.
Of the five appliance classes, plus lighting, that are considered for conversion to direct-DC, we assign an added cost to refrigerators, air conditioning condensing units, and central air supply fans. These are the largest end users in the sampled homes and would have the greatest added cost in converting to DC. In calculating these costs, we use retail prices from existing vendors as shown in Table 4 (DCAirco, 2014) (Home Depot, 2014) (B&H, 2014). Remaining appliances and lights are assumed to have a negligible effect on the overall cost of implementing DC.
The final additional cost considered in the proposed DC home is a bidirectional inverter. Because these devices are still uncommon, we estimate their cost as the combined cost of a rectifier and an inverter.
Figure 4 shows the levelized annual cost of electricity for each scenario as a percentage of each home's baseline annual energy bill (denoted as 100%). When solar PV is considered, annual electric cost decreases as a result of Austin Energy solar crediting, but there is the additional levelized annual cost of the PV array (shown here with Austin Energy installation incentives applied) and a system inverter. This results in a net increase in LAC of around 18%.

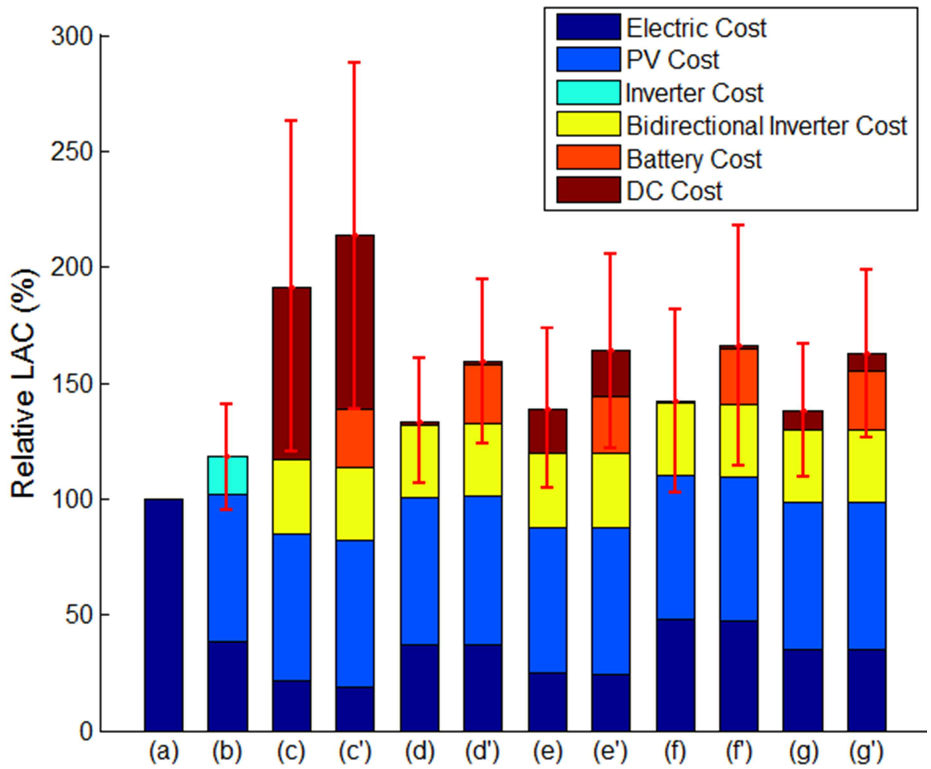

Figure 4. Levelized annual costs for the systems shown in Figure 2(a) through Figure 2(g). Primes indicate results with battery storage for solar generated energy. Results are shown as a percentage of a traditional (AC) home with no PV generation's annual electric bill. Bars show the mean result for each simulation. Error bars show plus or minus one standard deviation from the mean.

Whole-Home DC: Both whole-home DC scenarios see LACs roughly double compared to a home without a PV array due to the cost of outfitting an entire home with DC components and appliances. In the whole-home case, as well as all others, the addition of battery storage results in a small reduction in energy costs while adding a substantial capital cost that is largely not recovered.

DC Lighting: DC lighting simulations see an increase in LAC due to the added cost of the bidirectional inverter and small energy savings. DC equipment costs are small as only one circuit must be fitted with a DC-specific breaker and the cost of converting to DC LEDs is negligible when annualized over the life of the lamps. Power electronics make up a small fraction of the cost of an LED, so we do not expect the removal of a single rectification stage to significantly reduce equipment costs.

DC Condensing Unit: While DC condensing units deliver substantial energy savings, the cost of these units surpass cost savings and results in a net increase in LAC of 5-73% without storage and 22-105% with storage. Existing units are intended for rugged, off-grid, often mobile applications and have features not required for a residential installation. Thus, while the costs used here are high, they are reflective of the best currently available technology to serve a home's cooling load with variable speed BLDC motors.

DC Plug-in Electric Vehicle Charger: Similar to the conversion of home lighting loads to DC, EV chargers see minimal energy cost savings. DC implementation costs are also small as only one DC circuit is installed and the only hardware change at the charger is the removal of a rectification stage. The net results of these changes are an increase in LAC primarily due to the cost of a bidirectional inverter and storage, when applicable.

DC Refrigerator: A conversion to direct-DC supply of a refrigerator sees energy costs decrease, but the added cost of a bidirectional inverter and DC-compatible refrigerator result in a net increase in LAC of 11-68% without storage.

Cost Effectiveness of Savings: The overall cost effectiveness of each direct-DC configuration is plotted in Figure 5. The x-axes show total annual savings in kWh and metric tons of CO_2 calculated using the local grid emission factor shown in Table 4. The y-axis shows the cost added to each home's LAC to implement each solution. Coordinates show the mean of all homes in each simulation. Wide ranges of energy consumption baselines and solar PV system capacities across homes in the sample result in large variances that make presenting results with confidence bounds meaningless. For reference, houses in the sample have annual CO_2 emissions ranging from 1.1 to 19 metric tons. The mean result of solar PV installation in the sample was a net energy generation of around 6,200 kWh/yr per system that was offsetting grid generated electricity. This equates to an emissions reduction of around 3.4 tCO_2 per system per year. Without installation incentives, these systems add a levelized annual cost of around \$1,400/yr (€1,200/yr) per home. We use this level of cost-effective energy and emissions savings – observed as the slope of the line intersecting the solar PV marker (\$0.23/kWh or \$410/tCO_2, €0.20/kWh to €350/tCO_2) – to compare each DC simulation.

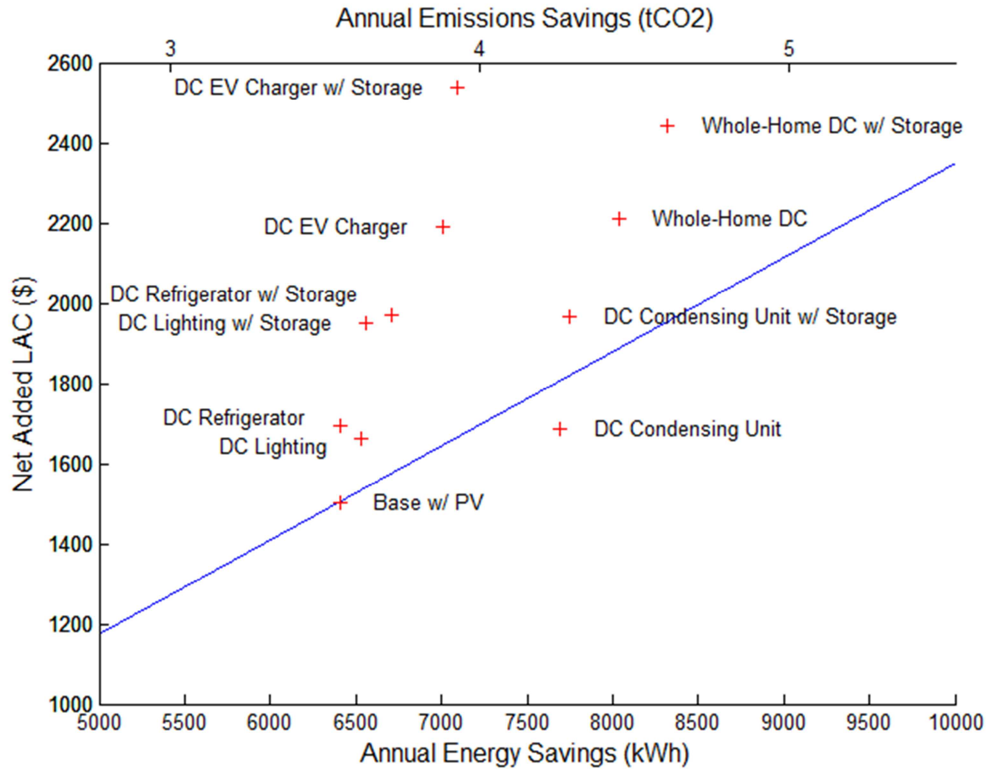

Figure 5. Cost-effectiveness of savings associated with each simulated DC home configuration. Annual energy and emissions savings are shown on the x-axes. The net cost added to a traditional AC home's LAC by implementing each scenario is shown on the y- axis. The blue line shows the cost-effectiveness (in $/kWh saved and $/tCO2 saved) of installing a solar PV array without considering any utility incentives. All values shown are the mean of all homes in each sample. Wide ranges of energy consumption baselines and solar PV system capacities across homes in the sample result in large variances that make presenting results with confidence bounds meaningless.

While all scenarios generate energy and emissions savings beyond what would be generated by solar PV alone, the added cost to achieve these savings is at a rate higher than implementing AC distributed solar PV alone in all cases but one. Solar PV arrays with direct-DC distribution to a condensing unit result in more emissions savings per dollar of added LAC than a traditional AC distributed PV array and condensing unit.

If over time the added costs of today's DC components and appliances were eliminated due to widespread deployment, the whole-home DC scenario without storage becomes cost-competitive with a home with a traditional AC-distributed solar PV array. The cost differential between a traditional system inverter and the DC system's bidirectional inverter is covered by the energy savings generated in this configuration. Because much of the energy savings and added DC system cost is a result of the central air condensing unit, the scenario where only this device is converted to DC is nearly cost competitive with traditional PV, showing only around a 4% higher LAC than a traditional PV array.

Conclusions

Results show that direct-DC distribution of solar PV power is a feasible means of generating energy and emissions savings in this sample of homes. However, at present costs only direct-DC supplied variable speed brushless condensing units match the cost-effectiveness in achieving these savings of a traditional solar PV array. These systems were found to reduce homes' baseline energy consumption and emissions by 7-17% while adding 18-78% to each homes' baseline LAC. In none of the simulated configurations was the added cost of battery storage for excess solar PV energy justified by the energy and emissions savings it provided. Given these findings, the continued growth of distributed solar PV generation, the increasing home electronic loads seen in recent years, and industry interest in direct-DC, it is likely that a very small number of such systems in homes may soon appear.

Policy Discussions and Recommendations

In light of these results, there is not a strong argument for an immediate large-scale deployment of direct-DC systems in any configuration other than DC condensing units at current component prices on the basis of reducing emissions. Given the cost-effectiveness of the savings these systems provide and the growing interest in direct-DC in homes, such systems may begin appearing in one-off system designs without universal standards in place as has been the case in direct-DC commercial lighting systems. Many aspects of such an installation would be without issue, but some significant barriers remain.

Under the National Electrical Code AC and DC systems under 600V are not explicitly differentiated, meaning a direct-DC home would pass existing building inspections (Savage et al., 2010). From an electric utility provider's perspective, all of the proposed system changes occur downstream of traditional meters so grid connection would likely not pose a challenge. However, Austin Energy's solar rebate program specifies that rebates and generation credits are administered based on AC capacity and AC generation (Austin Energy, 2014). It is therefore unclear whether a direct-DC PV array would be eligible for up-front equipment rebates. Also given the qualification that solar generation is credited per AC kWh, which assumes a conversion loss, any solar-generated DC power that is consumed in the home and not inverted to AC and sold to the grid would be undervalued with this program. If direct-DC systems gain more widespread adoption, utilities would have to respond to fairly credit this generation. Similarly, Austin Energy and other rebate programs for energy efficient air conditioning condensing units rely on certifications from the Air-Conditioning, Heating, and Refrigeration Institute (AHRI) for performance guarantees (Austin Energy, 2014). The manufacturer of the DC condensing units used here in modeling energy performance and cost does not have this certification, and it is likely that none of the certified units operate on DC. Obtaining this certification would allow early adopters of direct-DC condensing units the same benefit available to homeowners purchasing less efficient traditional condensing units.

In addition to these relatively minor issues, major nontechnical barriers to residential DC implementation remain and will have to be addressed before these systems gain more widespread adoption. Fortunately, experience with DC systems in data centers and the commercial market is growing. This has created a small industry of professionals with experience designing, installing, maintaining, and inspecting these systems. This knowledge base would have to be transitioned to a broader audience of engineers, electricians, and building inspectors to ensure that not only are the systems themselves safe, but that the image of direct current circuits becomes less foreign over time. Direct current may very well have a place in the residential sector, and research and development should continue to explore other potential benefits that might make a stronger case for a more widespread transition to what now appears a promising technology.

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Evaluating the long-term consumer experience and future expectations for energy efficiency enabling technologies in a smart homes context: a survey in Portugal

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Abstract

This paper highlights the results of a survey conducted on the residential sector, for households that had access to the same energy efficiency enabling product, were living in Portugal and used the product between 2012 and 2014. The survey design and development process was based on a collaborative effort by technology developers, business experts and product managers and was conceptually validated in cooperation with academia. Firstly, the survey conducted focuses on past consumer experience by surveying the value added by the different features of the product. Secondly, the survey focuses on collecting new insights regarding consumers' expectations on the forthcoming evolution of the product and associated business model. The data obtained reveals that although consumers find the technology easy to use, the features are mostly used in traditional web browsers for consulting information, as the majority of the technology users (40.8%) claim that they do not access the control features. In terms of future expectations the main priority for smart home services is in the field of Home HVAC Smart Control Systems (34.21%), Home Lighting Systems (27.63%) and Home Hazard Protection Systems (23.68%). In terms of willingness to pay, for the range of areas presented the majority of consumers revealed to be willing to pay up to 9 euros per month for each smart home service presented.

1. Introduction

Global efforts concerning the transition to a more sustainable world, coupled with the ongoing technological development, and increase of populations' living standards has been leading to the creation of value from a combination of visions, which involve environmental quality, economic development and social welfare increases. Henceforth driving change at various levels, with a strong impact on the way people interact and use basic resource, as is the case of energy. This transition to a smart, sustainable and inclusive economy is a priority in the European Union, through its 2020 agenda [1], which involves energy as a strategic pillar to achieve the broader level ambition. In terms of energy strategy the EU has proposed, and reinforced the 20-20-20 targets by 2020, including the increase of renewable energy by 20%, the reduction of Greenhouse Gases (GHG) by 20%, and the reduction of energy consumption by 20% [2], [3].

The above mentioned energy paradigm is central towards a low-carbon economy, its achievement involves the development of new products and services which enable the creation of new services and products which engage stakeholders to contribute to the efforts of a more sustainable energy system, therefore contributing to sustainable development in the long term. The process of developing new products and services and its contribution to the transition to a low-carbon world are dependent on the ability of these new technologies to engage its users and drive them towards more efficient use of energy resources.

The research presented in this paper focused on understanding the consumer experience to a product developed within the smart homes paradigm, providing home energy management features at the residential level. The research is based on a detailed survey that enabled the assessment of the consumer experience with the technology, as well as the identification of the consumer preferences for the future in terms of capabilities and willingness to pay for innovative services. The insights obtained from the process enable the validation of the consumer experiences with technologies developed for home energy management purposed, on a smart homes scenario.

The survey targeted consumers with a long-term exposure to the home energy management product, enabling the collection of information on the experience of consumer who have been interaction with the technology for a longer period of time, thus enabling the development of conclusions on what are the key value drivers for technologies with energy management features for the residential sector.

The paper presents a brief review of the smart home concept, and focuses on its contribution for home energy management (section 2), the methodology, which includes the survey design and development process is described (section 3), the main results are presented (section 4), and wider implications and conclusions are conveyed, and future work is proposed (section 4).

2. Smart Homes and Energy Management

From a conceptual standpoint the smart home is defined as an infrastructure with access to assets, communication, controls, data, and information technologies enabling the improvement of consumers wellbeing thorough higher levels of comfort, convenience, reduced costs, and interconnectivity of systems [4]. The necessary economic framework to exploit the capabilities of the smart home possibilities has been strengthened over the past decade, particularly from 2000s onwards, as consumers have widely and strongly embrace the era of mobile communications, which enables them to connect effortlessly to people and now in this context to their home, through monitoring, control and automation possibilities in various areas of the home [5]. From the breadth of possible use applications that the smart home enables, the following have been presented as the main categories in which the smart homes market is currently organised [6]:

- Energy efficiency: automatic monitoring and control of energy, water and gas consumption;
- Security: alarms systems, such as presence detectors and smoke alarms;
- Health: home care systems, ambient assisted living technologies, elderly care;
- Comfort: light control, heating and ventilation, entertainment systems.

The main areas presented above, represent the core areas of action possible in a smart context, these are similar to those presented by GSMA (*Groupe Speciale Mobile Association*) [5], consisting of security services, utility services, health services and media services. The figure below (Figure 1) represents the evolution of the smart home infrastructure departing from several standalone application towards an interconnected scenario, with interoperable systems that enable the creation of added-value services and application for the consumers benefit. The later enables the possibility of generating meaningful feedback on increasing the consumer awareness to its energy consumption and provides a framework for seamless action and automation.

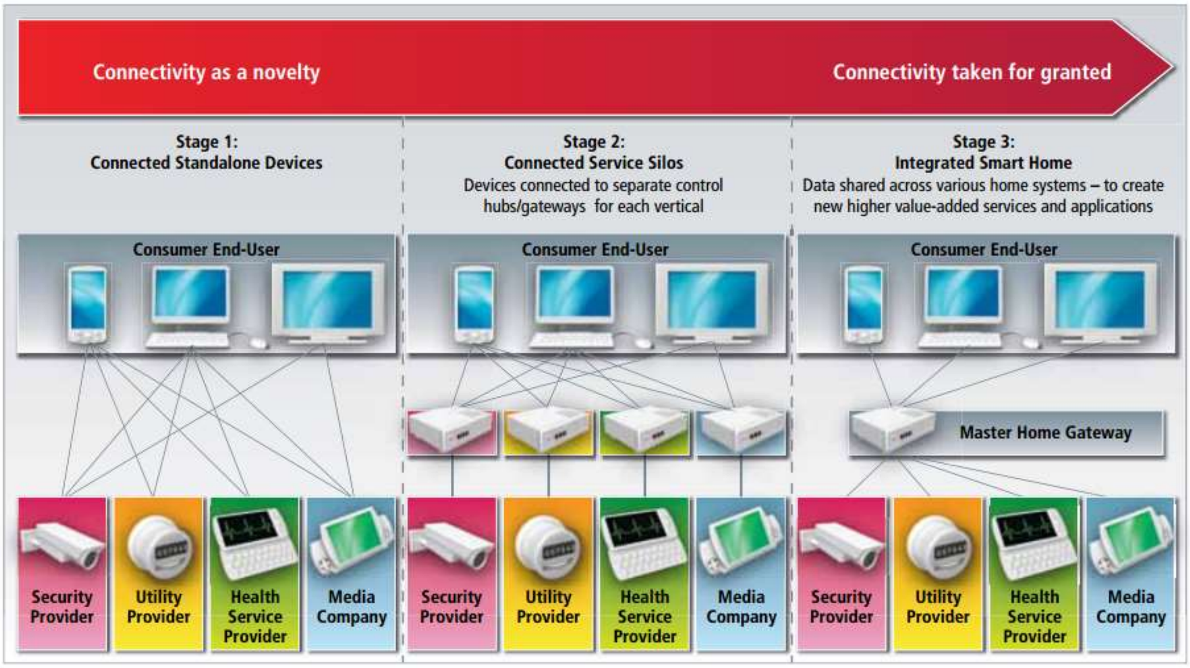


Figure 1 - Smart Home evolution, adapted from GSMA Vision [5].

From the various application possible through the smart home, focusing in the field of energy efficiency, the pace of development of the European market has been reinforced by the previously mentioned policy targets towards 2020. In addition to this framework the European Commission has presented in the end of 2014 a new framework of climate and energy goals by 2030 [7], which bring a new dynamic to the smart homes market, in particular for energy efficiency and home energy management application. The new proposed targets include a far more ambitious energy efficiency goal of 27% by 2030 [8].

Considering the successful delivery of the 2020 energy efficiency targets as well as the now proposed ambitious goal for 2030 the European Commission envision that each European citizen will have a smart meter to measure and communicate its energy consumption data, consisting of an investment of 45 Billion Euros from Member States for electricity and gas meters. These are vital part of the energy application within the smart home, which are now being stimulated through a strong policy framework at international level.

The development of the smart homes market, particularly for home energy management, beyond the positive impacts from policy frameworks in place is also stimulated by the ongoing momentum to promote energy savings as an opportunity for residential consumers to reduce their energy expenditures, whilst contributing to a cleaner environment with less energy waste. In the sense it is worth highlighting that consumers with the ability to control their home energy consumption, through smart home application are able not only to reduce energy consumption, or improve their consumption awareness, but also to control appliances and equipment remotely thus having an impact on comfort levels.

2.1. Home Energy Management Enabling Technologies

The home energy management enabling technologies most common today can be categorized according the level of control provided to the consumer [9]:

- Centralised Control, when the home energy management technology is able to communicate and control a range of devices at the home level, whilst allowing the user to control its home devices from a single location. For this level of control the most common system include, home lighting management systems and whole-home automation solutions;

- Device-Level Control, when the home energy management technology enables control actions at the device level, in this cases the user is able to control a single device. For this level of control the number of applications currently available increase and includes thermostat, smart plugs, smart power strips, lighting dimmers, and motion sensors.

- On-Board Control: when the control function for energy management is embedded in the device and/or household appliance. In this level of control the existing applications include smart light bulbs, as well as smart appliances that are able to respond to varying grid conditions or other constraints.

3. Methodology

The evaluation of the consumer experience was conducted through the development of a direct survey sent to a sample which has been exposed to a home energy management technology [10] for a period no less than 2 years. Herein considered long-term exposure to an energy efficiency enabling technology,

The survey developed was designed through an iterative process, as the authors have a combination of industry and academic experience, the final survey consists of a balanced approach to customer experience assessment designed to provide strategic insights on past experience, whilst providing indications on future possible trends.

The technology to which the customers have been exposed includes the following main features:

- Monitoring: the technology enables users to monitor their energy consumption at general level, and at the appliance level through the use of smart plugs;

- Control: the technology provides users with the possibility to control individual appliances through a smart plug;

- Interfaces: the technology is accessible through internet browsers, as well as through mobile application developed for Android, Windows and Apple mobile devices.

In order to enable a broader assessment, in combination with more specific feedback on particular technology features and how these impact the consumer experience the survey was developed in various blocks, as presented in the following figure (Figure 2).

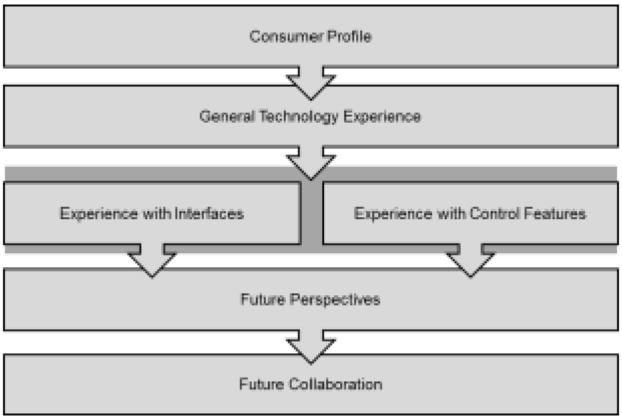


Figure 2 - Survey structure.

Considering the survey structure presented above (Figure 2). The consumer experience section was structured to collect relevant information from the respondent, its household and home characteristics. The General Technology Experience was based on general overarching questions focusing on the various components of the technology, enabling a blended perspective on the consumer experience as a whole. The survey sections focusing on interfaces and control features were created to enable the collection of more specific insights on how consumer use technology, as well as to understand what they value most. At last, the future perspectives section had as main goal to provide insights on the expected product evolution, as well as to enable participants to show their interest to participate in future consumer experience and product development actions.

The sample of customers involved in the study corresponded to 248 technology users, located in the Lisbon area, in Portugal, all of which have had access to the technology since 2012. The sample of customers was contacted by email and the survey was transferred to an online form to ease the process of collecting the replies.

The survey was first launched on the 2nd of February, 2015, and reminders were sent on the 9th and 11th of February. The survey was closed for answers on the 14th of February, 2015, corresponding to a period of 12 days online. The following section presents only the most important results of the various sections of the survey, representing the most meaningful insights for the evaluation of the consumer experience in a scenario of long-term exposure to the energy efficiency enabling technology.

4. Results

The survey launched in February, 2015 was online for a 12 day period and reminders were sent to respondents to ensure participation and a significant response rate. From the various contacts with the consumer it was possible to achieve an overall response rate of 30,65 % (i.e.: 76 full responses were obtained). The following table shows the evolution of the response rate for the period when a contact was made with the consumer.

Table 1 - Survey reply rate evolution.

Contact	Reply rate	Accumulated Reply rate
1st contact (Invitation for participation) Sent on 2nd of February, 2015	18,15%	18,15%
2nd contact (First reminder) Sent on 9th of February, 2015	10,48%	28,63%
3rd contact (Closing reminder) Sent on the 12th of February, 2015	2,02%	30,65%

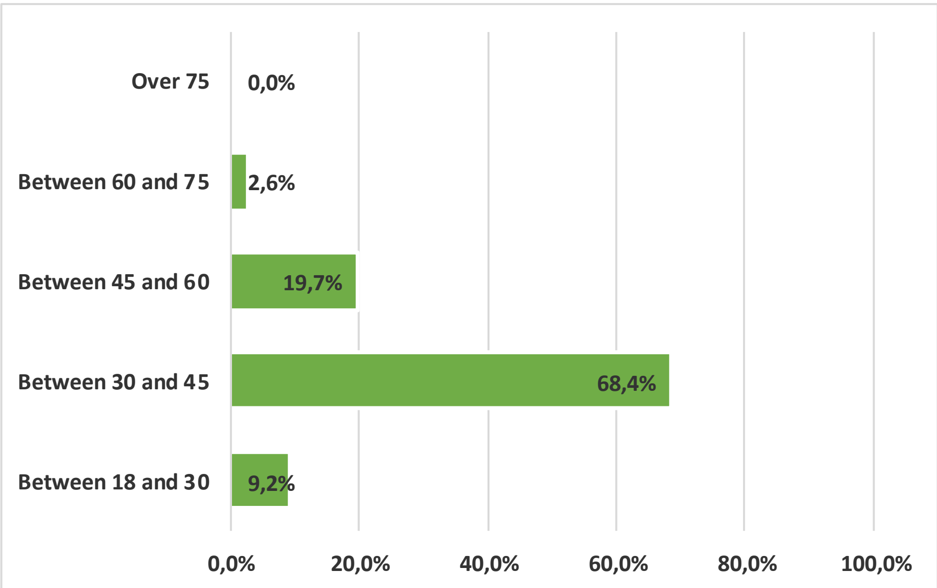
The reply rate evolved consistently as reminder where sent to the sample of consumers selected, hence validating the positive impact of nudging to increase the participation.

4.1. Consumer Profile

In terms of the general characteristics of the consumers, obtained through the *Consumer Profile* section, the following results were obtained.

From the responses obtained, 61.8% were from male customers and 38.2% where from female customers. However as households where of varying dimensions, the gender dimension is not used to infer trends on consumer experience.

In terms of demographics, the following graph represents the age range distribution of the respondents, with the majority in the age range between 30 and 45 years old.

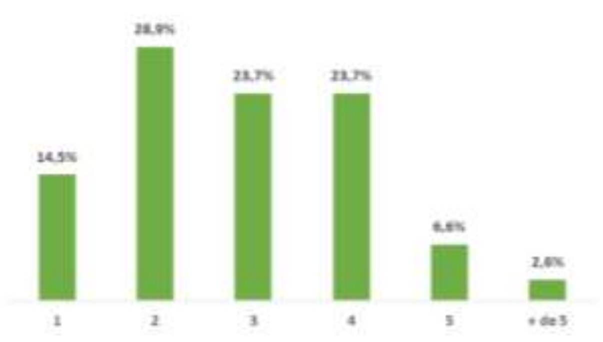


Graph 1 - Age range distribution

The majority of the obtained responses are between 30 and 60 years old, corresponding to a share of 88.1 % of the replies.

Regarding household dimensions the most significant share of the population has a household in between 2 and 4 members. For housing dimension the most common typology is a T3 (i.e.: a house with three bedrooms). The detailed responses for both household dimension and housing typology are presented in the following table (Table 2).

Table 2 - Household and housing characterisation.



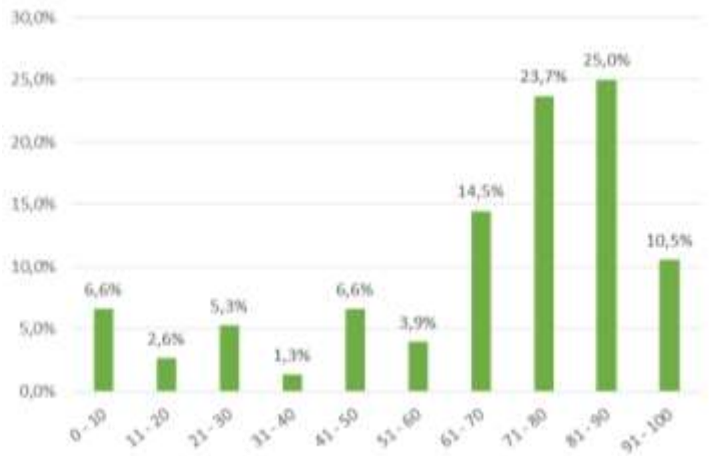
A – Household dimension, in number of people	**B – Housing size, in number of bedrooms.**

In terms of the consumer profile identified, the majority correspond to an average household as identified for Portugal [11]. The consumer profile information gathered is relevant for identifying the market segment, in terms of age, and households' characteristics for energy efficiency enabling technologies. The following section presents the main indicators on the general technology experience.

4.2. General Technology Experience

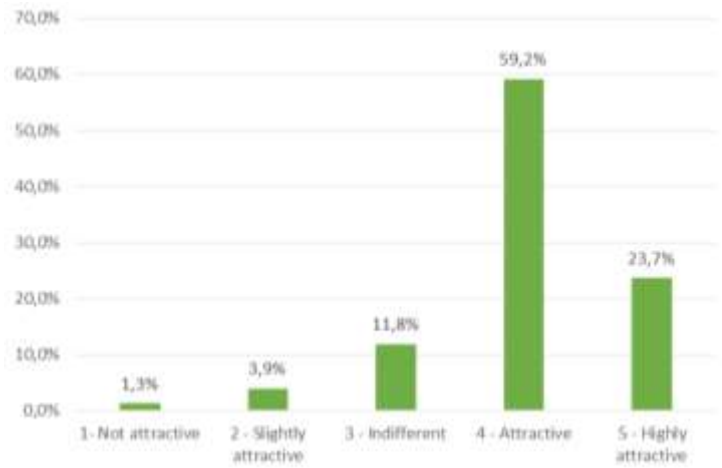
Considering the general technology experience, provided by the different capabilities of the technology presented earlier, which include monitoring, control and interaction interfaces for various platforms. The main general goal was to understand how satisfied consumer are with the technology they have for the past years. The questions included in this section included broad questions on the various technology features.

In terms of global satisfaction, on average the customer global satisfaction yielded a result of 68.94%. The following graph represents the distribution of the customer satisfaction obtained, as results ranged from 0% to 100%, these where clustered in 10 point levels (i.e.: from 0 to 10, from 11 to 20, etc.).



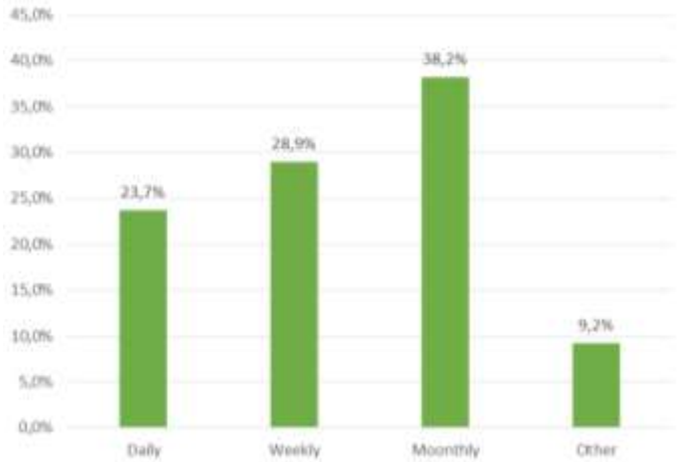
Graph 2 - Global consumer satisfaction.

Complementing the information on global satisfaction, customer where requested to rate the attractiveness of the technology, on a Licker Scale, from 1 to 5, being 1 the lower level of attractiveness and 5 the highest. From this enquiry 82.9% of the sample rated the technology either *Attractive* or *Highly attractive*, the distribution of the responses obtained is presented in the following graph.



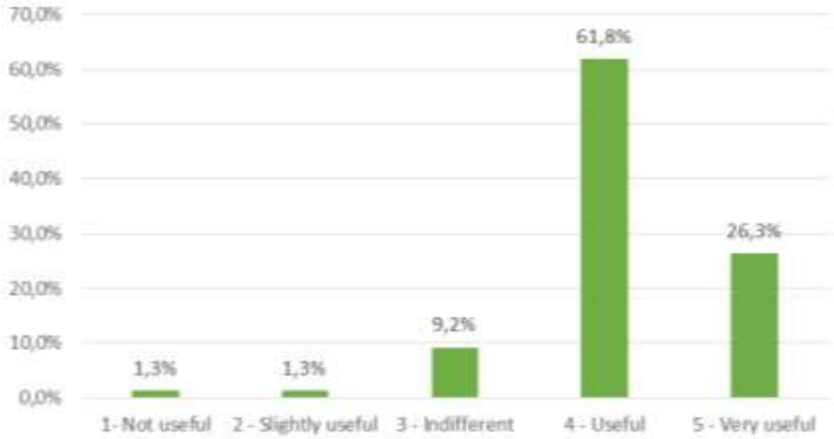
Graph 3 - Product attractiveness.

Considering that the energy efficiency enabling technology is present in the house and available for use, we were interested in understanding how often customers feel that the technology is useful for them. For this purpose the sample was enquired regarding the usefulness level, rated as useful on daily, weekly or monthly basis. (i.e.: consumer that access or interact with the technology on a daily basis, such as by consulting their consumption level or conduction control actions would rate the technology as useful on a daily basis.). For this question the majority of the customers rated the product as useful on their monthly routines, corresponding to 38.2% of the replies, potentially associated with validating consumption targets defined for the month, or for understanding the consumption of specific appliances and their impact in the electricity bill.



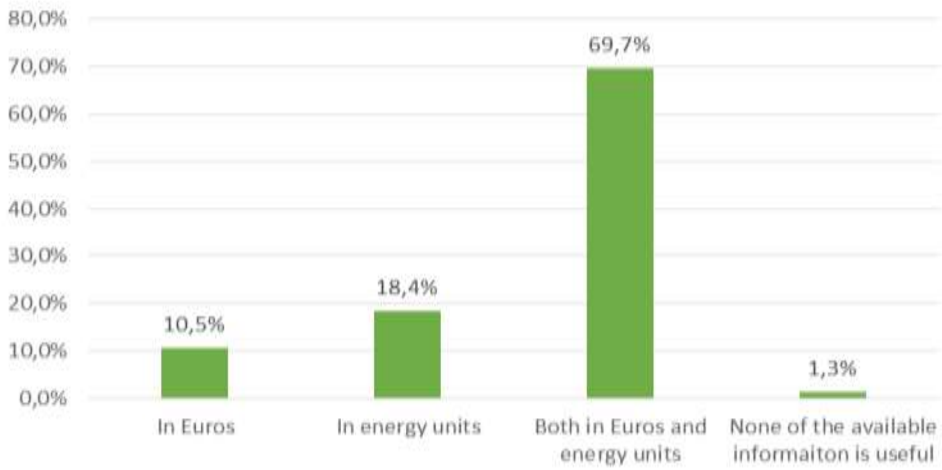
Graph 4 - Product usefulness for customers.

Whilst focusing on the usefulness of the technology, it was important to evaluate the particular usefulness of the information provided by the product. In order to confirm is the energy consumption related data generated helps users to better manage their home and their energy use. For this question 88.1% of the customers, rated the consumption information provided as either *Useful* or *Very Useful*, as presented in the following graph.



Graph 5 - Consumption information usefulness.

The concerns regarding the consumer experience and how their relationship is influence by the available information was further addressed by questioning the type of information that is more useful when consulting energy consumption levels. The available options for the sample to choose from where: (1) Information in euros, (2) Information in energy units, (3) Information in both euros and energy units, and (4) None of the information presented is useful. The results obtained are presented in the following graph. From the data collected, the majority of the consumers (69.7%) find it more useful to obtain their energy consumption information in both euros and energy units.



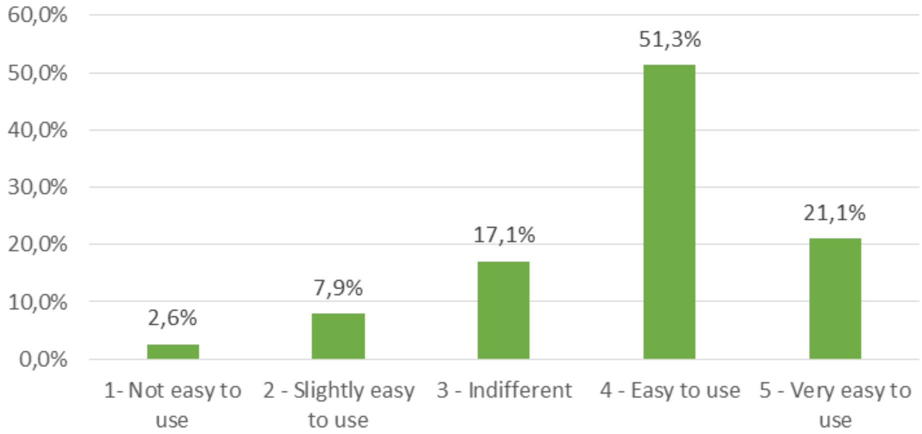
Graph 6 - Type of information usefulness.

In addition to the general customer experience assessment questions, more specific questions where presented to obtained feedback on the interaction with interfaces (i.e.: web interface, mobile application and in-home display), as well as with the available control features (i.e.: through the smart plug available.). The following sections present the main results from this more specific sections of the survey conducted.

4.2.1. Experience with Interfaces

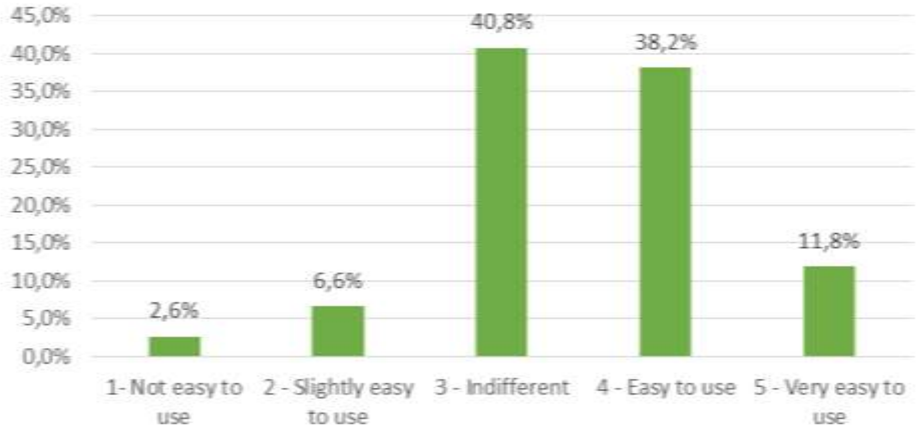
When evaluation the consumer experience with the product interfaces, we focused on obtaining detailed feedback on each existing interface. The data collected for this section focused on the user perception of ease of use of the technology, as a measure of the ability to obtain added-value from using and interaction with the interfaces. The assessment was based, as in the previous analyses in *Lickert Scales.*

For the web browser aces to the technology platform, than enables access to consumption data, as well as to control features, 51.3% of the consumers rated the technology as *Easy to use,* and 21.1% as *Very easy to Use.* The remained of the consumers' perspectives is presented in the graph below.



Graph 7 - Web browser experience.

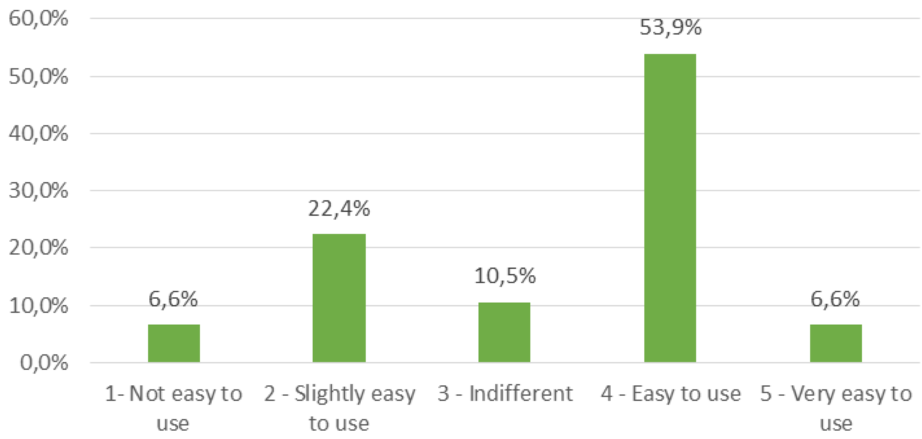
In terms of the consumers experience with the mobile application available, the obtained data contrasts with the web browser experience. For mobile applications (i.e.: mobile phones and tablet applications), the majority of the consumers' presented themselves as *Indifferent* regarding the ease of use, nonetheless 38.2% rated the mobile applications as *Easy to Use.* The remaining classifications are presented in the graph below.



Graph 8 - Mobile applications experience.

The insights depicted in the graph above (Graph 8) contrast with the generalised idea of the *mobile era*, where people are accessing information and services form their mobile devices. For this particular energy efficiency enabling technology customers seem to prefer web browser access. Nonetheless this may be due to particular population traits that were outside the scope of analysis of this research, which may be useful in future work assessing consumer experiences with smart homes technologies.

The analysis of the consumer experience with the in-home display, presents a less homogenous outcome, in one hand 53.9% of the consumers rated the technology as *Easy to use*, whilst 29% of the sample rated the in-home display as either *Not easy to use* or *Slightly easy to use.* Further results on the experience with this interface are presented in the following graph.

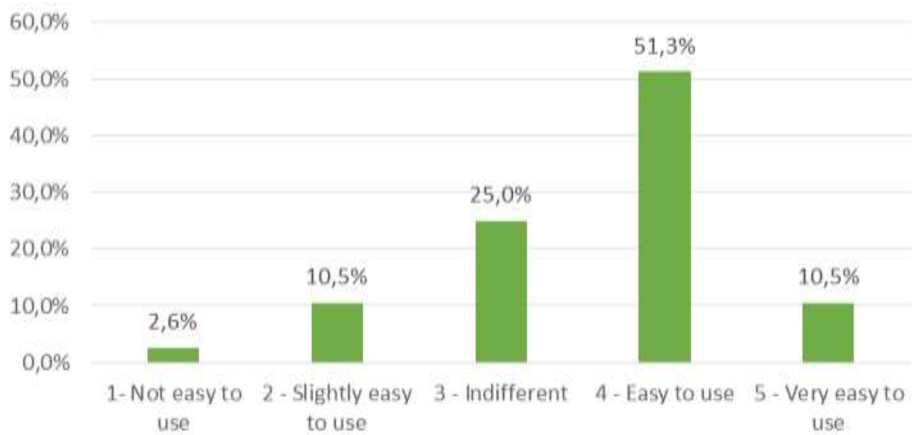


Graph 9 - In-home display experience.

In general the assessment of the experiences with interfaces presents better results for the web browser and mobile application, whilst providing fragmented insights on the consumers' experience with in-home display. This may be due to the static nature of the display, which is placed in one location of the house, when compared to web browser and mobile application which can be accessed in and outside the house through the internet.

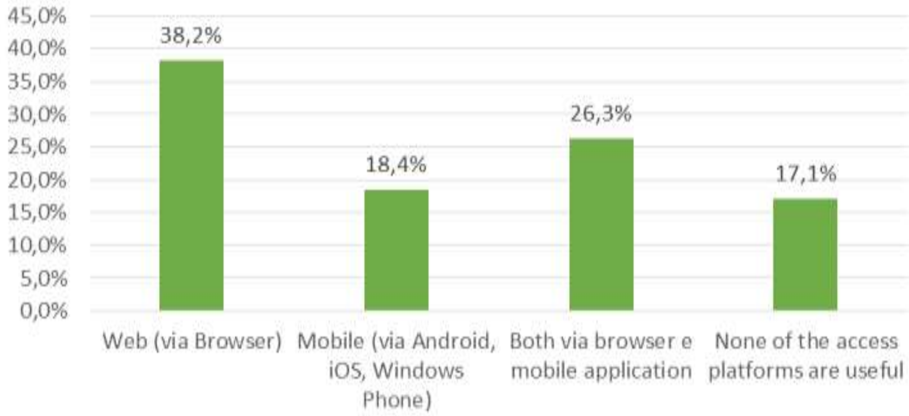
4.2.2. Experience with Control Features

On a similar approach to the one taken for the interfaces, consumers were approached with questions regarding the ease of use of the technology control features, which are possible through a smart plug device that enables appliance specific control and monitoring. For this technology features the majority of the consumers (51.3%) rated the control features as *Easy to use* and 10.5% as *Very easy to use.*



Graph 10 - -Control features experience.

To establish a bridge between the control features ease of use and the technology interfaces, consumers provided information regarding their preferred interface when initiating control related actions. The results obtained, presented in Graph 11, are in line with the results obtained on the interface experience assessment. For control features, the majority of prefer access via web browser (38.2%)



Graph 11 - Control features preferred interface of access.

Control features on the scope of the energy efficiency enabling technology require consumer action to trigger the control of the appliances. In this scenario consumers consider the existing control features easy to use. In spite of this, they do not use the control possibilities provided by the technology. When asked how often they access and conduct control actions on household appliances, 40.8 % of the consumers indicated that they do not access any of the control features of the technology.

The overall information provided in terms of past consumer experience with the technology portraits a general good fit of the technology features and capabilities and the ability of consumers to access and extract value from these features. Users find information useful In both energy units and monetary units, as while they consider the control features easy to use these are not accessed by most of the users.

4.3. Future Perspectives

Beyond the past experiences with the energy efficiency enabling technologies, the survey was designed to obtain feedback on new potential technology development roadmaps based on the users' perception of the priority of including new features and services as part of the current technology.

The areas of potential development presented to the consumer sample included: (1) ambient assisted living (i.e.: mobile health applications); (2) home security systems; (3) home heating, ventilation and air conditioning (HVAC) smart control; (4) home hazards protection systems (e.g.: fires, water leakages); (5) automated systems with learning capabilities; and (6) home lighting systems. Consumers rated the priority of each area of potential development as: Not a priority, Low priority, Indifferent, Priority and High priority.

The following table presents the consumers' expectations regarding the priority of the technological evolutions presented.

Table 3 - Future technology evolution perspectives.

Areas of evolution	Level of Priority				
	Not a priority	Low priority	Indifferent	Priority	High priority
Ambient Assisted Living	9,21%	18,42%	38,16%	26,32%	7,89%
Home Security Systems	2,63%	7,89%	25,00%	44,74%	19,74%
Home HVAC Smart Control Systems	0,00%	7,89%	13,16%	44,74%	34,21%
Home Hazard Protection Systems	1,32%	1,32%	23,68%	50,00%	23,68%
Automated Systems with Learning Capabilities	0,00%	14,47%	31,58%	40,79%	13,16%
Home Lighting Systems	0,00%	6,58%	18,42%	47,37%	27,63%

Focusing on the areas of evolution with more priority form the consumers' perspective, those with a higher share considered as a *Priority* are technological development which incorporate solution related with the Home Hazard Protection Systems (50% of the respondents), and Home Lighting Systems (47.37%). For the *High Priority* level the areas with most importance are development in the field of Home HVAC Smart Control Systems (34.21%), Home Lighting Systems (27.63%) and Home Hazard Protection Systems (23.68%).

In order to complement the future expectation on the technology development, the survey also served to collect indicators on the willingness to pay of consumers for smart home services that involve the areas they prioritised. The following table presents the results of the consumers' willingness to pay per area of development and is structured in 4 bands: Band A – between 1 and 9 euros; Band B – between 10 and 25 euros; Band C – between 26 and 40 euros and Band D – between 41 and 60 euros, the payment bands were presented as monthly fees for service.

Table 4 - Consumers' willingness to pay for future technologies

Areas of evolution	Consumers' Willingness to Pay			
	A - 1€ a 9€	**B - 10€ a 25€**	**C - 26€ a 40€**	**D - 41€ a 60€**
Ambient Assisted Living	71,05%	23,68%	2,63%	2,63%
Home Security Systems	64,47%	30,26%	2,63%	2,63%
Home HVAC Smart Control Systems	80,26%	15,79%	2,63%	1,32%
Home Hazard Protection Systems	78,95%	17,11%	2,63%	1,32%
Automated Systems with Learning Capabilities	84,21%	11,84%	2,63%	1,32%
Home Lighting Systems	82,89%	14,47%	1,32%	1,32%

In general terms the willingness to pay, for a monthly fee, for the areas of development presented is mainly in the Band A category. Consumers are willing to pay up to 9 euros per month for smart home related services. In spite of the majority of the consumer sample being willing to pay up to 9 euros, Band B represents a significant share of the population, those with greater share of consumers associated are Home Security Systems (30.26%), Ambient Assisted Living (23.68%) and Home Hazard Protection Systems (17.11%).

Following the future expectations section, participating consumers were invited to voluntarily provide their contact information to participate in future studies related to the theme of consumer experience and technology development for the smart homes context. Of the participating consumers 42.1% agreed to participate in future research actions centred in the consumer experience, this high share of interested participants highlights the opportunity associated with actively involving consumers in product and service development processes for the smart homes market.

5. Conclusions and future work

The conclusions of the survey launched are manifold in terms of the value provided to different players in the smart homes market.

- **Energy efficiency technologies developers have access to insights from a up-to-date study on consumer experience and expectations.**

From this perspective, technology developers should understand better the experience being provided to consumers in particular by mobile applications, as these did not yield results in line with the ongoing hype around the mobile application world. For the energy efficiency enabling technology, surveyed consumers revealed to user more the web browser access for consulting and controlling purposes.

- **Investors have access to potential indicators on what products to invest or not by considering consumer experiences on existing features, as well as future product development expectations.**

Venture capitalists, business angels and crowd-funders should look for innovative applications in the field of Home HVAC Smart Control Systems, Home Lighting Systems and Home Hazard Protection Systems. As these were the areas with a greater priority form the consumers replied obtained. When developing these new application the feedback obtained on the existing technology should be internalised to ensure that users benefit from the full extent of features and technology capabilities contributing to a better smart home experience.

- **Consumers' will be able to obtain other consumer's experiences on a mass market product, influencing the decision to acquire an energy efficiency enabling technology equivalent to the one evaluated through this study.**

From this viewpoint consumers are able to have a snapshot on how other users interact with innovative smart home technologies, for this case focusing on energy efficiency applications for home energy management. In this field consumers have the possibility to become more aware on how users take advantage of control features, which in this survey yielded a strong share of consumers claiming not to use the control capabilities, despite considering them easy to use. This information provides a good basis to direct consumers to choose products with lower consumer interaction needs, this is in line with the priority given by consumers to technological advances in the field of automated systems with learning capabilities, which can more autonomously than currently available technologies.

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Benefits and disadvantages of existing smart heating control systems: a critical survey.

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Abstract

Residential buildings are still responsible of a higher share of global energy consumption, in particular, the main amount of energy (68 %) is consumed for space heating and cooling. In this context, an important goal is the development of indoor climate control strategies that may help to reduce high-energy consumption. Thanks to the ICT development, the global market is already trying to answer to this necessity. A "smart home" should be equipped with computing and information technology, which responds to the needs of the occupants and works to promote their comfort, convenience, security. Several "smart heating" controls have been developed in the last few years, initially in American countries and after in Europe. In particular, these smart heating control systems act on temperature set points and schedules. The available "smart" control options and algorithms radically vary among the products presented in the market, shifting from memorization of user habits to interaction with other variables as windows openings and occupancy. This paper represents a survey of current temperature control systems available: they are compared and critically analyzed in their benefits and disadvantages. In particular, this study regards technical elements and heating system requirements, remote and smart control options, costs and installation procedures. Finally, possible upgrades are also considered in the perspective of a more persuasive technology and user awareness of energy consumption.

Introduction

In 2010, buildings still consumed nearly half of the total amount of energy used in Europe and, specifically, residential buildings have a share of 27% over 40% [1](BPIE, 2011). Consequently, a very important goal is to develop new climate systems and indoor climate control strategies that may help to reduce this high-energy consumption. Moreover, evaluations of energy efficiency schemes have provided increasing evidence of a "performance gap" between predicted and actual energy use following of energy efficiency measures. Current researches are following more efficient indoor climate control strategies that take into account occupants schedules and requirements, as well as, energy suppliers necessity. Domestic heating controls, such as radiator valves, thermostats and heating programmers, are the part of their heating system most used by consumers. Control systems, how they are understood, and how they are used, all have an impact on household energy use, occupants' bills and carbon emissions. In the face of rising fuel prices, better control of heating could lead to reduced energy bills for all consumers. They also influence users' comfort and sense of wellbeing since the feeling of control is important to people and their sense of wellbeing. When control is interrupted, it is likely to have an impact on how contented somebody feels in their property. Further, the success of energy policies rests on the usability of new technologies [2]. If usability has not been delivered for mature technologies, there are clear risks for consumers who take up new technologies.

Controls determine the length of time the boiler is operational, the flow rate of water through the boiler and the intensity of operation of the boiler all of which affect its fuel use and efficiency. Some savings relate directly to user behaviour: controls allow consumers to manage energy use by altering the temperature, duration and location of the heating they require. However, efficient controls, used correctly, can reduce energy use while providing the same level of heat. The Energy Saving Trust estimates that the average household could save 10 per cent of their heating energy use (£55/230kg CO_2 per annum) by turning their heating controls down by one degree Celsius [3]. This is based on adjusting the SAP energy efficiency assessment calculation to assume a temperature of 19 rather than the default 20 degrees. One of the main benefits of programming controls is ‘setback’, reducing the temperature when out or sleeping. A 2011 US field trial [4] found that of various behaviour changes reducing the heating system set back temperature overnight had the greatest impact on energy consumption: for each degree Celsius increase in temperature, there was an increase of 520 kWh in energy consumption annually for the typical building modelled. A bimodal heating pattern, where the home is heated during two periods in a day, has been shown to be more efficient than continuous heating. On the other hand, different heating controls system were developed in world market in the last few years, previously in U.S. and afterword in Europe. Heating controls allow users to easily regulate the temperature of their home. The controls automatically turn heating on and off based on settings input by the user to ensure maximum comfort. This process moves away from a fixed, traditional timer system and can therefore be used to better control the temperature within buildings. An important, often overlooked fact is that by installing other efficiency measures in residential buildings (such as cavity wall insulation or loft insulation) more heat gets trapped in the home; so people often just accept their home is warmer. However, to see savings in energy bills, the temperature of the home needs to be kept the same as it was before – then the heating system will have to work less hard to keep it at the required temperature and therefore users will use less gas / electricity. In this study several heating control systems were critically analysed and compared in their benefits and disadvantages. Some of them present a higher level of system complexity and possible controls, while other have a wide chance of upgrade. Nevertheless none of them results fully accessorized.

Behavioral context

Several studies have compared internal temperatures in buildings with different sorts of heating controls. Shipworth et al., (2010) [5] found no significant difference between the average maximum temperatures of living rooms with and without standard heating controls over an entire heating season. More recently Kelly et al. (2012)[6], working with the same researchers, performed a more detailed analysis of the how the same internal temperature data varied across the entire year whilst controlling for key co-variates like external temperatures. This more sophisticated analysis did show some key differences. Mean daily internal temperatures were lower in homes with thermostats (0.24°C on average) or TRVs (0.17°C on average) than homes without them and increased with the temperature setting of the thermostat. Notably however, they found no significant difference in internal temperatures for homes controlled manually compared to those controlled with a timer or programmable thermostat. The authors conclude that it is not the presence or absence of particular controls that is important, but rather how people choose to interact with the technology that really matters. A recent literature review [7] found that consumers find heating controls difficult to use and many do not use them effectively. It highlighted that the elderly and those in local authority housing were more likely to find their controls difficult to use and that tenants were less likely than owner-occupiers to have a full set of standard controls (thermostat, timer and TRVs). The literature review suggested the UK market has failed to deliver the potential from standard heating controls because installers select which controls to install, not end-users, so there is no market demand for manufacturers to design more usable controls. It advocated a standard to ensure heating controls are usable and a central information resource to inform consumers. Findings from the user requirements gathering and usability testing could begin to fill this gap. In the US, modelled savings overestimated actual savings leading the market to promote heating controls as an energy efficiency measure, only to scale back support when better evidence emerged. Inaccurate assumptions [8] about how people heated their homes lead programmable thermostats to be established within the ENERGY STAR® program in 1995 and utilities to offer rebates for their purchase. However, they were removed from the California IOU program in 2006 and the scope of the ENERGY STAR® thermostats program was reduced following evidence that high potential savings were rarely achieved. There are even reports of evaluations that show homes in the USA with programmable thermostats consume more energy than those relying on manual thermostats [9]. In the US, inflated claims of savings from programmable thermostats persisted for many years, qualified by statements that these relied on devices being “used properly”.

Common used domestic heating controls

Householders typically only interact with three types of control: room thermostat; the programmer (sets on/off times of heating; hot water may be on the same or a separate time schedule) and thermostatic radiator valves (TRVs). Typical central heating timers allow consumers to set times for the heating system. This model has the same schedule for heating and hot water. Each can be timed, permanently on or permanently off, independently. Although most homes now have most of the controls shown above, the degree of control can vary considerably depending on the age of the system. A typical level of flexibility offered by a room thermostat, programmer and TRVs would be two or three periods per day for heating and hot water (either with the same times or different time schedules), with the option of different schedules for weekdays and weekends. Usually heating and hot water can also be set to permanently 'on', permanently 'off'. When timed, some systems allow the heating or hot water control to be 'advanced' to the next 'on' or 'off' state, e.g. to turn on heating early. Some controllers also have a boost setting for an additional one, two or more hours. Programmable thermostats are widely used in many parts of the world for both heating and cooling control, and many studies on domestic controls relate to these. Although available in the UK, few are at present installed. These devices combine the functions of the wall thermostat with a system timer. They allow different temperature values to be set for different time periods, for example a night 'set back' temperature of say 12°C to stop the building becoming too cold. This is not usually necessary in the UK due to a temperate climate, where the system is usually either on or off with a temperature separately set by the wall thermostat.

Heating controls by household type

The review looked at how the installation of primary heating controls might vary across household type40, including tenure. Table 5 (below) summarises the data.

Household type	Primary heating controls (weighted percentages)			
	Room Thermostat (%)	Central Timer (%)	TRV (%)	Full set of controls (%)
Householder under 65	76	98	67	49
Householder 65 and over	80	96	64	49
Number of people in household				
One	76	95	59	43
Two	77	98	69	51
Three	74	98	70	52
Four	79	99	66	50
One family household				
Couple	79	98	69	53
Couple with dependent children	80	98	69	53
Tenure				
Owner occupied	78	99	67	50
Private rented	68	97	58	38
Local authority	79	92	70	56
Registered social landlord	82	95	72	58

Table 5. Proportion of household types that reported having primary heating controls

Source: EFUS (2011/12); n=2356 weighted and scaled to represent the English housing stock of 19,700 thousand households with central heating.

The figures indicate that households living in private rented accommodation are significantly less likely to have a full set of heating controls than owner occupiers, or those in local authority or registered social landlord properties. They are less likely to have room thermostats and less likely to have TRVs fitted to radiators. The figures for the size of household suggest some smaller, but still significant differences amongst one person households; they are less likely to have Thermostatic Radiator Values (TRVs) fitted, and less likely to have a full set of heating controls than larger households. The differences were not explained, at least within the EFUS sample, by larger proportions of single people living in private rented accommodation.

Attitudes on heating controls

Energy Saving Trust and Department for Communities and Local Government (DCLG) (2010) highlight a range of potential motives for householders to install better control systems. They can help users save money and avoid waste, increase wellbeing and comfort, make people feel good about themselves by providing a sense of control and make life easier by providing more convenient control. It suggests that environmental motives may be secondary, due to a lack of direct link perceived between control use and environmental results, something also suggested by focus group results.

Some of these motives are reflected in survey responses from consumers who had bought new or replacement heating controls. Saving energy was reported as a major driver by 78% of those who had bought programmers and 59% of those who had bought TRVs, followed by saving money (74% programmers/57% TRVs) and environmental concern (57 per cent/45 per cent).

The qualitative research do not clearly give an indication of the set or actual temperature highlights the complexity of the controls, indicating difficulties on the ‘thinking’ scale of inclusive design. It found controllers which:

- make unclear use of abbreviations and terminology, for example, ambiguous programme titles
- have illogical positioning of buttons
- lack of feedback on user activity (users do not know whether their change had been registered by the system)

Research found that users could be confused about relationship between controls and heating systems, as well as the most efficient way to use the controls. Some thought it is most efficient to switch water and space either heating on and off, manually or using a programmer, whereas others (around 30 per cent) leave their heating on constantly and use their thermostat and/or TRVs to achieve desired comfort levels. Other research findings highlighted that many users understood how they used heating affected their energy consumption others did not realize that turning down the thermostat would reduce energy consumption. Moreover, there is a lack of consensus about whether intermittent or continuous use of central heating is more efficient. Some users admitted to a lack of interest in how their controls worked, while some others reported opening windows while using the heating without considering the energy efficiency impacts.

Smart heating controls

Traditional heating control systems use preset time intervals to avoid heating the home when its occupants are away or asleep [10, 11]. However, since these systems use static settings, they cannot adapt to the actual occupancy pattern of the household. For this reason, heating control technologies are developing rapidly to include: remote control via the internet or mobile phones; sensors that can detect occupancy, open windows or doors, external temperatures; advanced heating algorithms that can learn occupant habits and preferences. Without government intervention innovation could focus on improving convenience and comfort rather than saving energy, potentially inducing the adverse effect of increasing energy use.

The idea of using information and communication technology to automatically and “intelligently” control heating systems has been investigated for several years. Well-known examples of such smart heating approaches include the Neurothermostat [12], the GPS Thermostat [13], the Smart Thermostat [14] and several others [15, 16, 17, 18, 19]. The first few commercial products – such as the NEST learning thermostat, tado and EcoBee’s Smart-Si – have recently started to appear.

Requiring users to explicitly provide feedback about their behavior has proved to be a very inefficient means of performing heating control [11]. Users simply do not have enough (monetary or comfort-driven) incentives to engage with the system. Default settings are often left unchanged. As a result, systems based on explicit user feedback may even induce an increase in energy consumption [10, 11]. In contrast, recent studies have shown that systems using occupancy detection can allow for about 30% in energy savings with respect to traditional timer-based systems [10]. However, such systems require instrumenting the home with dedicated, special purpose sensors. Although the installation of such additional sensors may be simple and inexpensive [10], it still requires user intervention and commitment, and poses additional system challenges such as configuration and calibration.

A smart heating system should meet two main requirements. First, it should significantly reduce the amount of energy spent on heating (compared with conventional room heating systems). Secondly, it must ensure adequate thermal comfort – which the ANSI/ASHRAE Standard 55 defines as “the condition of mind that expresses satisfaction with the thermal environment" [14, 20]. The smartness of the system typically lies in its ability to adapt to current environmental conditions, the specific household characteristics and the behaviour of the occupants. The difference between a conventional automatic (or programmable) heating system and a "smart" one is that while the former operates according to a pre-defined and typically deterministic (e.g. timer-based) schedule, the latter typically adapts its control strategy to the user context. In both cases, though, the heating is controlled automatically, i.e. with the aid of a thermostat that does not require explicit human intervention.

The industry has recognized usability issues; as a result, two strands of new product are evident. The first can be characterized as retaining time and temperature setting as a manual activity using the controls described above, but improving their usability, i.e. making it easier to program control settings. These can be described as 'active' smarter heating controls. Active Smarter Heating Controls typically provide consumers with greater control by enabling the local and remote control and management of temperature, time and zone. So, for example products at this level of development might include deploying a hub unit that is connected to the household broadband internet service. The thermostat and time programmer are wirelessly linked to this hub via the internet to the vendor's servers. The user is then able to configure all their time and temperature settings from their home computer or tablet through an interface that includes prompts which aim to assist them in making consistent and efficient settings. Many suppliers also provide a smart mobile phone application to do the same job. The second strand of product development sets out to automate some or all of the parameter setting process so that the task of adjusting times or temperatures is wholly or partly lifted from the user. As a consequence, physical intervention by the user is needed less frequently to maintain efficient settings, enabling the user interface to be further simplified. Passive systems are characterized by technologies that seek to control heating by learning about a consumer's heating behavior or by delivering the same or similar amount of comfort by use of less energy.
Products in this strand of development typically aim to automate time setting by detecting occupancy and household activity using a variety of sensors. The system then uses the data collected to build a predictive model of occupancy patterns. Occupancy is then translated into heating times taking account of building thermal properties. Temperature setting can also be automated given knowledge such as the household demographics and the weather.
According to different dimension of usability, the most important dimensions identified for heating controls are: vision, dexterity and thinking. Position is an important fourth element. Research covered TRVs, room thermostat, digital and analogue programmers and programmable thermostat.
The smart heating control systems mentioned above were compared and critically analysed in their benefits and disadvantages. In particular, an excel matrix was created in order to visualize all the characteristics together and allow a rapid comparison. This study identified technical elements for the hardware system, heating system requirements, remote and smart control options, costs and installation procedures. Finally, possible upgrades are also considered in the perspective of a more persuasive technology and user awareness of energy consumption.

The main technical element for smart thermostats' category is the thermostat itself. Many devices already present into the market have integrated in the base kit sensors in order to monitor the indoor environmental characteristics (temperature, humidity and lux level). They also have a movement sensor in order to detect occupancy. They can connect to the weather forecast on internet to have information about outdoor conditions. In order to use it, the existing heating system should be controlled already (or be refurbished to be controlled) with a low voltage thermostat. If the plant is designed for both heating and cooling (e.g. heat pumps), the thermostats could manage all seasons. A Wi-Fi connection is needed in the home in order to allow the remote controls and the weather forecast connection. Control systems where sensor are not included in the base kit require more electronic devices that have to be inserted in the house. All of them present a gateway in order to communicate on one side with internet connection and with the several devices on the other. For example, systems have got a boiler receiver to be placed on the boiler and a thermostat for the heated environment, others control the heating system through thermoregulation valves. A fundamental presence is a boiler as heat generator or heating units with TRVs as references. The majority of the system could be installed by a qualified installer o DIY. The professional installation is suggested of course if there is not already a boiler control unit or wired.in thermostat. It is better to consider professional installation in case of a multi-zone system with different heating (radiators, heating floor).

Smart thermostats display several automatic controls. The most known it is their capacity to record heating and cooling setting, set up by the occupant during the first week of use, in order to make an automatic regulation of the heating/cooling system. The activity sensor allowed them to turn off the heating/cooling system when occupancy is not detected. Very interesting are the automatic controls supplied by Nest (only for specific energy suppliers).
Also other systems have some automatic controls. Thermo-regulation valves (like Micropelt or Qivicon) turn off the heating system when occupancy is not detected or the windows are opened. It is of interest the automatic control provided by Tado: if a smart phone is connected to the system, it gives the possibility to activate a geo-localization service so that the heating system is automatically managed considering occupants' location.
Almost each system presents its peculiarity. Nest allows to control 10 thermostats with a single account in order to manage 2 houses or a multi-zones control for the single home. British Gas, because of its direct control to the boiler, can also manage hot water production. Tado is developing a control system for air conditioning units.
Qivicon is the only thermal energy control system that actually is integrated in a whole-building control system for lighting, shading installations, electric and electronic devices as well as security system. Ecobee also produces smart plugs that can be controlled by the same account. Furthermore, Ecobee also sells a control system for office building that controls an unlimited number of thermostats. As it has already been said, Micropelt thermostatic radiator valves can normally be remotely controlled only by a thermostat, but they could be connected to a Building Management System for a remoted control as well. Furthermore, these valves are interesting since they are alimented by thermal energy without the need of batteries.

System control option related to houses characteristic

These systems control the central heating boiler, hot water (tank storage) control is optional. Hot water control is featured for turning hot water on and off to fill the tank at a set time, or in more advanced systems an add-on thermostatic kit sets the temperature in the hot water tank. In case of large detached houses, or large apartments, multi-room or zoned heating should be considered as a possible solution in order to heat only the rooms really occupied. Multi-room heating control is allowed in different ways. It could be used wireless thermostatic radiator valves which sense the temperature and activate each radiator individually - they can be grouped together into zones around the home, along with underfloor heating controls. It also supports electric underfloor heating as its own zone. On the other hand, smart thermostat could also provide multi-zones control: a thermostat should be installed in each zone to control. A single account could control until 10 thermostat. The thermostat could be installed in 2 different houses as well in order to control also the vacancy house.

Remote and Smart controls

All the other systems can be controlled in remote through an application for smartphone and tablet or an account on internet. Hive offers just four temperature change points while for the other systems the temperature set-point changes are practically unlimited.
The majority of them allow real-time information and control, as well as, the definition of several schedules. For some of them, the schedules could be set over an annual calendar, considering holidays and the presence of guests. Furthermore, individual schedule could be defined for different occupants. Most systems provide via internet also weekly or monthly reports to the occupants about the indoor environmental conditions and the heating activities. Some of them make interactions among the different data monitored and they report which are the influence factors that drive to a higher heating activity.

None of reviewed system have implemented the thermal accounting. Nest and Green Momit express energy saving in terms of heating hours saved; British Gas provides an online application to its costumers on which people can insert their thermal and electric energy consumption (monthly accounting) in order to obtain seasonal energy reports and to compare them with other British Gas customers.

Smart heating control systems' Costs

Table Title

Column Title	Column Title
Table text	Table text

Prices for smart energy systems range around 300 euros. The up-front cost of the kit is not the only cost that should be considered: the installation option, as well as the annual fee are other costs that should be taken into account. Many of the systems stress the possibility for a do it yourself installation but they suppose that final users have the skills and confidence to deal with wiring boiler and thermostat. Nest, Hive, Evohome, Heat Genius, Tado, have installation options, ranging from 50 euros for the relatively simple Hive, to approved installers who will quote each job separately. Heat Genius currently has a free installation offer, with no end date set as yet. Honeywell Evohome, Heat Genius and Tado all come in close to £250 for the basic kit alone, and each has its benefits, with Evohome and Heat Genius boasting multiroom control (at an extra cost), while Tado claims it's smart and easy to use.
On the other hand it is also important to consider the pay-off in term of energy saving produced by the different systems. Multi-room systems, like Evohome and Heat Genius, have the greatest potential for cutting energy spending by heating only the rooms you need. Learning systems such as Nest, Heat Genius and Tado could easily outsmart manual scheduling, especially by switching off when the house is unexpectedly empty.

Smart and social heating control system: Social awareness implementation

Three controls systems are studied to give more feedback to the users in relation to thermal performances of buildings and their behaviour . Nest provides a monthly energy report that gives some tips for a more energy saving use of the heating/cooling system, allows users to see the mean values of set-point temperature among all USA and create a competition among users based on energy saving behaviour detected by thermostats. British Gas developed an application for its customers on which people can insert their thermal and eletric energy consumption (monthly accounting) in order to obtain seasonal energy reports and to compare them with other British Gas customers. On the other hand Ecobee tries to give some information to the users about their houses' performances.

Evidence gaps in surveyed sistems

In addressing a general gap in evidence related to most areas within this domain, this section of the review lists evidence gaps and highlights areas which could plausibly be filled by a field trial were one to be conducted. Whilst the review identified some reports of field trials, the majority are US based evaluations of programmable thermostats. Some of the key issues identified in US research are pertinent; in particular, the role that usability of heating controls plays and the need to monitor consumer behavior when assessing the impact of installing new controls. However, the fact remains that there is a gap in the evidence with regard to UK research to assess whether heating controls affect energy demand. Shipworth et al. suggest that the lack of robust empirical investigations into this issue is attributable, at least in part, to the lack of national data on central heating demand temperatures and durations. The authors argued that evaluation of the impact of heating controls on energy demand requires accurate data on the temperatures people heat their homes to, and the amount of time people have their central heating turned on.

An evidence gap also exists with regard to the role of consumer behaviour in potential relationships between energy saving and domestic installation of improved control technologies. Evidence reported in this review and additional analyses of the EFUS data suggests that up to 25% of households with central heating systems with a central do not use it to control when the heating is switched on or off. However, as the paper by Malinick and his colleagues discussed114, it may be wrong to assume that people using manual controls are universally failing to use their heating systems in an energy efficient manner. A further gap in knowledge concerns the availability of robust, independent information on how people are using heating controls, linked to outcome data on heating demand temperatures and durations. As noted earlier in the review, an important strand of new product development has set out to automate some or all of the parameter setting process so that the task of adjusting times or temperatures is wholly or partly lifted from the user. Described by some authors as 'smart'117 or 'passive' heating controls, these systems automate time setting by detecting occupancy and household activity using a variety of sensors. Because these systems are so new, evidence of efficacy certainly represents a gap; research has so far collected very little in the way of independent evidence to test their impact on energy savings relative to more conventional controls.

Hive system has got a wide possibility of upgrade, such as more heating time zones during the day, and multi-room heating support. It uses the Zigbee communication standard so there's no reason it couldn't interact with other devices in your home. Nest seems to be more flexible product: it already combines with the Nest Protect smoke and carbon monoxide alarm to better detect people in your home and shut down your heating if there's a rise in CO. Tado launches an air conditioning control system which is complementary to its central heating control, and as another Zigbee-based system it could communicate with other devices. The modular nature of Evohome suggests a broader range of applications. Heat Genius, Ecobee, Cosy include optional smart sockets, which will remotely switch on and off any devices connected to them, which opens the door to other automated devices. Cosy company talks about integrating temperature and consumption data, as well as multi-room and hot water control.

The following figure resumed the characteristic that an ideal heating control system should have.

Heating control system requirements:		
1.	*IEQ Monitoring*	Indoor temperature
		Indoor Relative Humidity
		Outdoor Temperature
		Solar Radiation
2.	*Remote Control*	Schedule setting
		Real time control and information
3.	*Auto Control*	Occupancy and window opening
		Learn from habits
		Geolocalization & smart temperature control
4.	*Energy Reports*	Report: Annual, monthly weekly data (IEQ and heating activities)
		Thermal energy accounting
		Comparisons with similar users

Ideal Heating system requirements

Conclusion

Since heating represents the major source of energy consumption in domestic environments, significant energy savings may be achieved. The system will opportunistically leverage smart devices, such as smart electricity meters and mobile phones, to estimate occupants' activity patterns and thus optimize the heating control strategy.

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Buildings

Impact of appliances and lighting for Nearly Zero Energy Buildings (nZEBs) in Europe

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Abstract

As established by the recast of the European Union (EU) Directive on Energy Performance of Buildings (EPBD), all new buildings should be nearly zero energy buildings (nZEBs) within the EU by the end of 2020. However, reaching this result at the lowest possible cost remains an important challenge. Balancing renewable power generation with energy efficiency will be vital in Europe.

We describe results obtained from the use of energy optimization software *BEopt* developed at the U.S. National Renewable Energy Laboratory. The model performs detailed hourly sequential simulations using the energy performance software *EnergyPlus* showing how to best achieve very low or zero energy home designs at the lowest possible cost in 36 representative locations across Europe. We have adapted the model to run using European hourly climatic data, using relevant construction methods, cost data and unit energy consumption. A novel aspect is the inclusion of the likelihood of future climate change relative to cooling loads estimated. This anticipates building design changes necessary to address the challenges to be faced in a changing world.

A key finding of the research is that energy reductions of 80% and beyond are economically feasible for new construction, although the mix of selected measures varies strongly with climate. Results show that a broad approach to efficiency mixed with renewables performs best, while a narrow focus on building thermal performance can be counterproductive. In particular, we illustrate how exclusion of lighting and appliances results in sub-optimal solutions, especially for electricity use which has a disproportionate impact on greenhouse gas emissions.

1. Introduction

Residential and commercial buildings are globally estimated to consume approximately 40% of primary energy and to be responsible for 24% of greenhouse emissions [1]. Achieving annual nearly, net or positive buildings have been demonstrated in many monitored projects in Europe. In particular, very low energy homes have proven the Passivhaus approach, although the trade-off of incremental measures against best appliances and renewable energy generation has not completely addressed.

The Energy Performance of Buildings (EPBD) Directive, together with the Energy Efficiency Directive (EED) (EU, 2012/27/EU) and the Renewable Energy Directive (RED) (EU, 2009/28/EU), set out a package of measures to create the conditions for significant and long term improvements in the energy performance of Europe's building stock [2][3][4][5].

A nZEB is defined as a building that "has a very high energy performance with a low amount of energy required covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby". Article 9 of the EPBD recast states that Member States (MS) shall ensure that new buildings occupied by public authorities and properties are Nearly Zero Energy Buildings (nZEBs) by December 31, 2018 and that new buildings are nZEBs by December 31, 2020. Furthermore, the Directive establishes the assessment of cost optimal levels related to minimum energy performance requirements in buildings. The importance to integrate the nZEBs concept into National Building Codes and International Standards is widely recognized [6].

However, the EPBD recast does not specify requirements, or details of the calculation of energy performance. Consequently, it will be up to MS to define what "a very high energy performance" and "to a very significant extent by energy from renewable sources" exactly constitute for them. Other open issues concern how to combine nZEBs with the requirement to optimize the investments involved and the associated reduction in energy costs; and how to carry out performance level calculations in each country [7].

In order to address this need, we identify an approach to harmonize efficiency and the use of renewable energy sources in specific locations.

2. Research Objectives

Nearly zero energy buildings (nZEBs) have to combine efficiency, thermal improvement measures and renewable energy sources (RES) production. The authors attempt to address this issue through the use of a comprehensive building energy simulation tool which considers European weather data linked to a cost database followed by an exhaustive optimization approach. nZEBs, for the purposes of our study, are defined as buildings saving 90% of source energy for all end uses in reference to a baseline case. The main key points of this approach are:

- The methodology is aimed at identifying the lowest cost path to reach the nZEB target;
- Hourly weather data is used for selected European locations;
- A detailed thermal analysis model is performed to derive space heating, space cooling and water heating consumption;
- Both building thermal performance and appliance efficiencies are taken into account in the analysis;
- Renewable energy electricity production is directly compared to the cost of energy savings by efficiency technologies;
- Costs of competing components along with their life expectancy, replacement costs, salvage value etc. are evaluated in a detailed way;
- Results are compared to varying construction techniques, materials, equipment, energy costs, and other performance parameters variations for sensitivity analysis;
- Location results allow the identification of the most suitable cost-effective methods to reach nZEBs in European Member States (MS).

We used the BEopt & EnergyPlus simulation programs to identify how to reach Nearly Zero Energy Buildings (nZEBs) at the lowest possible cost. BEopt uses the Energy Plus and TRNSYS simulation programs for its calculations of the savings of specific options in the optimization process.

2.1 Building Energy Simulation

BEopt is an Energy simulation tool, able to include an economic evaluation in the optimization model. It is possible to evaluate both new and existing building design and to consider how component properties influence the optimal choices for house retrofits. The calculation model in *BEopt* uses the renowned hourly energy simulation EnergyPlus developed by the Lawrence Berkeley National Laboratory and the U.S. Department of Energy [8].

This model estimates hourly household heating, cooling, water heating and appliance loads within EnergyPlus. Fundamental building thermodynamics are estimated via finite difference conduction functions using a multi-zone representation that allows a robust evaluation of transient thermal phenomena. A variety of energy carriers can be simulated. The simulation has been indexed to real buildings to verify its potential to replicate measured energy use in cold versus hot climates [9].

The simulation model has been adapted to run in European climates by adding hourly IWEC weather data files, converting to metric inputs and adapting cost data to the European format. Using similar inputs, favorable comparisons have also been produced against the Passivhaus Planning Package (PHPP) software [10]. Solar thermal and solar photovoltaic (PV) system output is evaluated using the state-of-the-art TRNSYS simulation [11].The economic optimization method is consistent with established procedures for nZEBs cost-optimality in the EU. BEopt contains a library of approximately

150 energy efficiency options. The software's optimization method sequentially searches for the most cost-effective option across a range of categories (walls, floor and ceiling insulation levels, window glass type, HVAC type, etc.) to identify the optimal building design able to reach the target performance at the lowest cost.

To enable the optimization, a library of measures is defined with their characteristics as well as their specific costs, life expectancy, operation, maintenance, and replacement costs. Renewable energy production is evaluated using a photovoltaic (PV) simulation (Transient Simulation Program: TRNSYS) as well as prediction of solar water heating performance. For a given location, this allows the cost effectiveness of energy efficiency measures to compete directly with the cost of renewable energy production to determine the most convenient path to near zero energy. Even in cold climates, this method offer some advantages against the standard *Passivhaus* approach as it is possible to reach zero energy performance at a lower cost [12].

The optimization model evaluates the entire suite of options and selects the option with the highest present value savings. It incorporates this option, and re-simulates all available options. The process continues in this manner until a benefit cost ratio of lifecycle savings is reached or until zero energy is achieved using RES. The sequential search technique has a number of advantages. Not only does it attempt to reach the established target, but it does attempt to locate the least expensive path to achieve that target. It further locates intermediate optimal points along the path, i.e. minimum-cost building design at different energy savings levels. Another advantage is that discrete building options are evaluated, reflecting realistic construction options. This means that specific materials, equipment and appliances are evaluated given realistic features of available products. Finally, near-optimal alternative designs are also identified within the optimization process.

2.2 Economic Parameters

In all locations, many measures have been selected from available ECMs. The simulated energy demand from each energy carrier together with cost data are used to analyze the cost effectiveness of individual measure.

Cost effectiveness calculations are based on the present value of life-cycle costs and last over an analysis period of 30 years. The procedure for estimating life-cycle cost calculations are well documented **Error! Reference source not found.**. The assumed economic parameters are shown in Table 1 for Milan.

Table 1. Economic Parameters for Optimization.

Category	Rate
General Inflation Rate (GR)	2.0%
Energy Price Inflation Rate (ER)	3.0%
Financing Interest Rate (MR)	5.0%
Discount Rate (DR)	5.0%
Down Payment with Financing	10.0%
Current Electricity Price	€0.25/kWh
Current Natural Gas Price	€16.10/ GJ or €0.058 kWh_{gas}

They are based on recommended guidelines supplementing Directive 2010/31/EU [14]. The assumed costs, service lives, and maintenance fractions for each of the hundreds efficiency measures considered are given in an Excel linked to the simulation. The value of the energy price inflation rate implicitly approximates the EU Emissions Trading scheme with carbon pricing assumptions of 25€/tCO_2 in 2020 to 39€/tCO_2 in 2020.. Although the selected rates are based on the E-C guidance, we performed sensitivity for the Milan optimization case, given current prevailing conditions in spring 2015, which suggest lower inflation and financing rates. The new parameters for sensitivity are: General Inflation Rate (GR) 1.0%, Energy Price Inflation Rate (ER) 0.5%, Financing Interest Rate (MR) 4.0%, Discount Rate (DR) 4.0% [15].

It is possible to alter the input parameters to consider very long time horizons and/or higher energy inflation rates. The optimization can also be limited to non-equipment options, providing a better evaluation of one-time interventions, such as those related to envelope insulation.

Energy costs for electricity and natural gas are taken from [1]. No financial incentives have been assumed for either efficiency or renewable energy sources. However, differing measure life is specified for each measure. For instance, most insulation measures are assumed to last at least 50 years as opposed to renewable energy systems. These systems might last 20-30 years and require operation and maintenance during that time as well as replacement before the end of the analysis period. A key leverage point in the analysis is that if PV electricity system is specified, its cost effectiveness becomes the key economic test for other competing measures, which should be installed before the PV system is considered. However, in our analysis, the PV system has been often installed midway through the optimization process with further efficiency measures still needed at the end to achieve the nZEB target.

2.3 Analytical Approach to Climatic Variation

The optimization of both building energy efficiency and solar power production requires incorporating specific data on climate severity and solar irradiance in a location. Appliance efficiency also plays a part in this optimization since improved appliance efficiency alters building internal heat generation rates and the resulting heating and cooling. However, important is the relative need for heating and cooling in that location as indicated by its climate.

For the analysis we selected locations across Europe in order to have at least one representative city of each MS. Other cities were added for comparison in order to have a good geographic coverage of possible climates. Given the very large degree of climatic variation, we simulated 36 locations spread across the various countries. These data came from the IWEC hourly weather tapes that are then used by EnergyPlus simulation to predict heating and cooling, and by TRNSYS to predict how solar power production varies over time. The simulated locations are listed in Table 2.

Table 2: Simulated locations

Location name	Country
Amsterdam	Netherlands (NL)
Athens	Greece (EL)
Berlin	Germany (DE)
Bordeaux	France (FR)
Bratislava	Slovakia (SK)
Brussels	Belgium (BE)
Bucharest	Romania(RO)
Copenhagen	Denmark (DK)
Debrecen	Hungary (HU)
Dublin	Ireland (IE)
Geneva	Switzerland (CH)
Kaunas	Lithuania (LT)
Kiev	Ukraine (UA)
Koln	Germany (DE)
Larnaca	Cyprus (CY)
Lisbon	Portugal (PT)
Ljubljana	Slovenia (SI)
London	Great Britain (UK)
Madrid	Spain (ES)
Marseille	France (FR)
Milan	Italy (IT)
Moscow	Russia (RU)
Munich	Germany (DE)
Oslo	Norway (NO)
Paris	France (FR)
Palermo	Italy (IT)
Prague	Czech Republic (CZ)

Rome	Italy (IT)
Salzburg	Austria (AT)
Seville	Spain (ES)
Sofia	Bulgaria (BG)
Stockholm	Sweden (SE)
Stuttgart	Germany (DE)
Tampere	Finland (FI)
Vienna	Austria (AT)
Warsaw	Poland (PL)

3. Prototype New Residential Building Characteristics

The methodology approach is now illustrated for Milan (Italy). A standard new house of 120 m^2 above grade with a full cellar has been considered. This building is derived from a prototype described in a recent study by Ecofys GmbH and the Danish Building Research Institute [16]. Its main characteristics are summarized in Table 3. The same table reports system properties, insulation levels, airtight equipment efficiencies and appliances. This building is assumed as a standard energy performing starting point for the optimization process of this research. We chose a baseline of 80% incandescent even though lighting is currently in a state of rapid change in the EU. It must be noted, however, that the lighting segment is so cost effective that even assuming a 30% saturation of incandescent, that change to CFL/LED would still be among the first measures chosen within the optimization.

Table 3. Characteristics of the baseline building used in the Optimization.

House Size	120 m^2 over 2.5 m cellar containing heating equipment	
Neighbors	Similar neighboring buildings on the two sides of the house	
<u>Envelope</u>		
Windows	23 m^2 with double clear glass (~2.2 W/m^2K)	
Walls	R 1.3 Insulated perlite filled masonry walls (~0.8 W/m^2K)	
Attic	R-5.3 insulation (~0.18 W/m^2K)	
Doors	Insulated wood entry door (~0.8 W/m^2K)	
Air Leakage	Standard construction (4 ACH at 50Pa blower door pressure)	
<u>System</u>		
Heating	Hydronic natural gas heating system, 82% efficiency	
Cooling	COP 4.1 mini-split cooling system	
T Set point	20^{o}C for heating, cooling 23^{o}C	
Hot Water	155 l insulated boiler in cellar providing 120 l per day at 55^{o}C	
Mechanical Ventilation	20.3 1/s continuous with 72% efficient ERV	
<u>Appliances</u>	A+	Option A+++
Refrigerator	340 kWh/yr.	201
Cooking	334 kWh/yr.	302 (Induction)
Dishwasher	319 kWh/yr.	258
Clothes dryer	0.98 kWh/kg	0.59 kWh/kg
Clothes washer	183 KWh/yr	150 kWh
Lighting	80%incandescent: 600 kWh/yr	100% CFL/LED: 175 kWh/yr
<u>Renewables</u>		
PV System	None	4.0 kWp with 95% efficient inverter
Solar Hot Water	None	6m^2 closed-loop system

We used a water heating load of 120 l/day. The size of the potential PV system (4.0 kWp) has been chosen based on available south facing roof area, selecting efficient modules and allowing the possibility for installing a 6m^2 solar water heating system. According to [17], temperature in Europe is likely to increase in the near future. Considering that the simulated new buildings would be used for decades, we consider adjustments to simulation assumptions to account for this change. Typically, for evaluating cooling loads in residential buildings, a thermostat cooling set-point of approximately 25 °C is assumed. To compensate higher cooling loads in future, we adopted a set-point of 23 °C. This change is in line with recent climate predictions [18], but it is still a measure that provides an indication of the importance of addressing cooling loads in future buildings in European housing stock. This accounts for the likelihood that cooling loads could grow over Europe with warmer temperatures.

Also, we include a mini-split cooling system as available in the optimization analysis in the prototype building of all locations. This has the important advantage of carefully considering options that might reduce heating, but adversely impact cooling loads. The exclusion of a cooling system would have favored options that may lead to overheating.

4. Simulation Results

When simulated in Milan (Italy) the baseline new building is estimated to use 3901 kWh per year and 54.3 GJ of natural gas for space and water heating (space heating is approximately 44 GJ). The optimization process is designed to find the most cost-effective set of energy efficiency measures related to envelope, appliances, and systems. Measures are evaluated against the cost of electricity and natural gas, considering the cost of producing solar electricity using roof-top photovoltaics.

Table 4 shows the selected measures from the analysis conducted in the Milan example to reach the final design configuration. Beopt and EnergyPlus ran a total of 2097 simulations in 43 iterations to get to the final target of 90% and beyond source energy savings. As shown in the table, selected options comprise insulating walls to R-7.2 (0.14 W/m^2K), improving ceiling insulation to R-10.6 (0.09 W/m^2K), insulating the cellar walls on the interior (0.29 W/m^2K), reducing building air leakage to 0.6 ACH at a 50Pa blower door pressure (Passivhaus standard), a 98% efficiency fully condensing gas boiler with improved pipe insulation, 100% efficient lighting and a complete selection of A++ appliances (refrigerator, dishwasher, clothes washer, dryer). An electric feedback system with an automated system to shed plug loads is also selected. During the optimization process, a 4.0 kWp grid-connected PV system is added. It produces all the electricity needed at the site.

Our example analysis shows the capability to achieve more than 95% source energy savings in Milan with cost effective measures. This results in lower annualized costs for combined energy and investment costs when paying for the upgrades. Table 5 also shows the changes to electricity and natural gas use, source energy consumption, incremental and cumulative costs compared to the baseline.

Table 4. Selected Order of Energy Effciency Measures for the Optimization in Milan (Italy).

Case	Category	Measure	Total GJ	Electric (kWh)	Gas (GJ)	Increm. (€)	Cum. Total (€)
1	Base Case	None	103.4	3901	54.3	0	0
2	Appliance+	A++Dryer + Win:Dbl_LE_LowG	99.4	3365	56.1	250	250
3	Appliance+	Eff. Lighting+ Lt. tile	97.1	3115	56.7	320	570
4	Appliance+	A++Refrig	95.8	2963	57.0	160	730
5	Appliance+	A++Clothes Washer	93.2	2808	58.3	150	880
6	Wall Ins.+	Walls: +R3.3, 3 ACH50	73.0	2685	39.0	1177	2057
7	Windows+	40% Glz to south, Induction rnge	72.4	2655	38.8	75	2132
8	Distribution	Hydronic piping to R-2	72.0	2647	38.5	39	2171
9	Air Tightness	2 ACH50	70.5	2647	37.1	107	2278
10	Air Tightness	1 ACH50 + Hi Eff Mini-split	66.8	2582	34.3	325	2603
11	Mech. Ventilation	90%+ ERV	64.9	2550	32.9	349	2952
12	Heating Sys.	98% eff. fully condensing boiler	61.5	2550	29.9	392	3344
15	Air Tightness+	0.6 ACH	61.1	2553	29.4	134	3478
16	Roof Finish	Dark Tile	61.0	2562	29.2	0	3478
17	Ceiling Ins	Insul to R 6.7	60.5	2559	28.8	202	3680
18	Appliance	A++ Dishwasher	59.8	2515	28.7	160	3840
19	Windows	Dbl_LE_HiGain_Ar Fill	59.3	2518	28.2	148	3988
20	Solar PV	4.0 kW PV system	19.2	-1014	28.2	14484	18472
21	Windows	Dbl_LE_Hi gain_Air Fill_Ins frame	17.8	-1005	26.8	546	19018
22	Water Heat	Fully Condensing Gas WH	16.6	-1005	25.6	429	19447
23	Cellar Walls	Cellar Wall : +R1.8	15.8	-994	24.9	447	19894
24	Ceiling Ins	Ceiling to R8.6	15.8	-996	24.6	286	20180
25	Wall Ins	Wall to R 6.3	12.8	-1017	22.3	2246	22426
26	Wall Ins	Wall to R 7.2	12.0	-1020	21.6	782	23208
27	Appliance	Feedback & home EMS	9.7	-1275	22.2	620	23828
28	Cellar Walls	Cellar W to R 1.6	9.3	-1269	21.7	1732	25560
29	Ceiling Ins	Dbl_LE_HiGain_Ar Fill	9.1	-1272	21.5	-986	24574
30	Windows	Dbl,_LE,_HiG_Ins_frame_ArFill	8.2	-1266	20.8	751	25325
31	Cellar Walls	Walls to R 3.5	7.9	-1260	20.5	456	25781
32	Solar Hot Water	Solar water heater (6m²)	4.9	-1108	16.0	4800	30581

*The cost of improving the heating system boiler and hi-efficiency cooling system changes over the course of the BEopt analysis. The cost of the fully-condensing boiler is that before sizing advantages are incorporated.

** The incremental costs of more efficient refrigerators and other appliances were obtained by comparing standard versus A++ product costs within a single manufacturer. Note that incremental costs may be higher when comparing across manufacturers.

The sensitivity analysis performed on the economic parameters for the Milan case show that, although the order of the measures selected in the optimization and the final NPV are changed, the lower rates do not change the final selection within the optimization for the achieved energy savings reduction. The lower inflation rates actually result in a lower annualized cost of energy and financing costs (final point on the curve goes from 2470 € to 2363 €).

Within the optimization, the first group of selected measures are dominated by low or no-cost options (such as roof finish solar absorptance), by choice of A++ appliances and efficient light. These measures are highly cost effective and associated with a very steep drop in the annualized costs.

Moreover, the building begins with equally distributed glazing, but the simulation later determines that moving the glazing area to the south face of a building — a no cost option for a new construction — is highly desirable.

Additional wall insulation shows very large energy reductions within the optimization. The optimization process spend much time parametrically analyzing more than a dozen window options with varying glass coatings, solar transmittance or G-factors, fill and framing types. The selection changes over the optimization when heating and cooling system sizes and efficiencies are altered. It is interesting to note, however, that as the building improved thermally, the incremental cost of more efficient heating and cooling systems become negligible as the required size is reduced.

The final selected package of measures has a total incremental cost of 30581 €. 14484 € of this amount are for a 4.0-kWp PV system and 4800 € are for a pumped solar water heating system that augmented a 98% fully condensing gas boiler. As seen in Table 4, the efficiency measures dominate the potential cost effective savings. Thermal building improvements greatly reduce gas consumption while appliance and lighting efficiency improvements are key factors to cut electrical energy use.

The efficiency improvements reduce household natural gas use by 71% (55 to 16 GJ annually) and electricity consumption by 38% (3901 to 2424 kWh/yr). After efficiency improvements, a 4.0 kW PV system is able to produce an amount of electricity (3532 kWh/yr) that is 1108 kWh more than the improved building annually requires. The combined total annual source energy needed, considering both efficiency improvements and renewable power generation, is cut by 97% with a similar corresponding reduction in annual CO_2 emissions from the household from 6.0 to 0.2 tonnes.

There are also large financial advantages having a thermally efficient building with solar electric power production. The homeowner annually saves approximately 2243 € the first year in utility costs (bringing the annual utility cost to less than zero) and, even after accounting for interest expenses, the owner has a positive cash flow in. A comparison between the baseline and the optimized building related to simulated initial annual consumptions for electricity and natural gas is summarized in Table 5. Table 5 also shows the changes to electricity and natural gas use, source energy consumption, incremental and cumulative cost when compared to the baseline. It may be noted that these costs for appliances were based on data on actual models within an average manufacturer and there may be variances across manufacturers. Solar PV production from the PV system, annual net electricity consumption, and savings are also reported for the simulated nZEBs in the 36 locations.

Table 5: Simulated Initial Electricity, Natural Gas and PV electric output for the Baseline and Optimized Nearly Zero Energy Buildings in the 36 Locations

IWEC Location	---- Base Building ----		---- Optimized Near Zero Energy Building ----			
	Annual Electricity (kWh)	Annual Natural Gas (GJ)	Solar PVH (KWh)	Annual Net (kWh)	Natural Gas (GJ)	Source Savings (%)
Amsterdam, NLD	3482	60.2	3437	-1210	15.2	97%
Athens, GRC	4938	18.4	5358	-2521	12.5	120%
Berlin, DEU	3537	65.1	3371	-1152	18.6	93%
Bordeaux, FRA	3574	36.2	4270	-1832	16.2	104%
Bratislava, SVK	3798	59.3	4051	-1838	21.0	102%
Brussels, BEL	3532	59.9	3115	-841	16.4	92%
Bucharest, ROU	4112	56.9	4660	-2090	21.7	100%
Copenhagen, DNK	3491	73.7	3476	-1257	20.6	93%
Debrecen, HUN	3860	60.6	4191	-1955	21.8	99%
Dublin, IRL	3441	59.0	3309	-1143	14.6	97%
Geneva, CHE	3731	54.4	3963	-1785	19.9	99%
Kaunas, LTU	3579	84.7	3418	-1155	18.7	95%
Kiev, UKR	3669	74.5	4138	-1829	21.2	98%
Köln, DEU	3523	60.7	3288	-1005	16.9	93%
Lamaca, CYP	5334	11.1	5985	-2708	12.7	123%
Lisbon, PRT	4103	16.7	5413	-2831	13.0	128%
Ljubjana, SVN	3719	64.8	3572	-1254	18.8	94%
London, GBR	3470	55.0	3487	-1263	13.9	99%
Madrid, ESP	3889	33.9	5200	-2732	18.1	114%
Marseille, FRA	4174	31.0	5209	-2630	14.0	118%
Milan, ITA	3901	54.3	3532	-1108	16.0	95%
Moscow, RUS	3640	92.1	3412	-1111	21.5	92%
Munich, DEU	3546	73.0	3831	-1545	20.2	96%
Oslo, NOR	3508	83.9	3142	-894	19.5	92%
Paris, FRA	3590	52.6	3605	-1471	18.3	97%
Palermo, ITA	5015	11.4	5457	-2397	11.6	121%
Prague, CZE	3523	76.5	3239	-1023	15.9	95%
Rome, ITA	4373	24.2	4862	-2468	12.5	119%
Salzburg, AUT	3590	64.1	3593	-1348	17.5	97%
Seville, ESP	5035	12.9	5730	-2855	10.2	130%
Sofia, BGR	3757	59.3	3614	-1272	16.8	96%
Stockholm, SWE	3508	85.6	3326	-1090	18.9	94%
Stuttgart, DEU	3558	65.4	3743	-1445	17.7	97%
Tampere, FIN	3526	101.7	3361	-1087	23.4	91%
Vienna, AUT	3687	63.5	3801	-1518	17.6	98%
Warsaw, POL	3567	74.6	3447	-1146	21.4	92%

From data in Table 5, we see that natural gas use varies with heating with a factor of 6:1 from the lowest consumption location (Palermo) to the highest (Tampere). Electricity consumption varies less (1.6 to 1.0), being elevated in warmest locations. Photovoltaic output from the rooftop PV system varies approximately with a factor of 2:1 from the sunniest location (Seville), to the cloudiest (Brussels). Figure 1 graphically illustrates initial and optimized building electricity consumption together with net annual optimized electricity and solar PV output in each location.

From the tabular data above, we see that natural gas use varies with heating severity by 6:1 from the lowest consumption location (Palermo) to the highest (Tampere, Finland). Electricity consumption varies less (1.6 to 1.0), being elevated in the warmest locations. Photovoltaic output from the rooftop PV system varies approximately 2:1 from the sunniest location (Seville, Spain), to the cloudiest (Brussels, Belgium). Figure 2 graphically illustrates how initial, optimized building and net annual electricity compares to the solar PV output for each location.

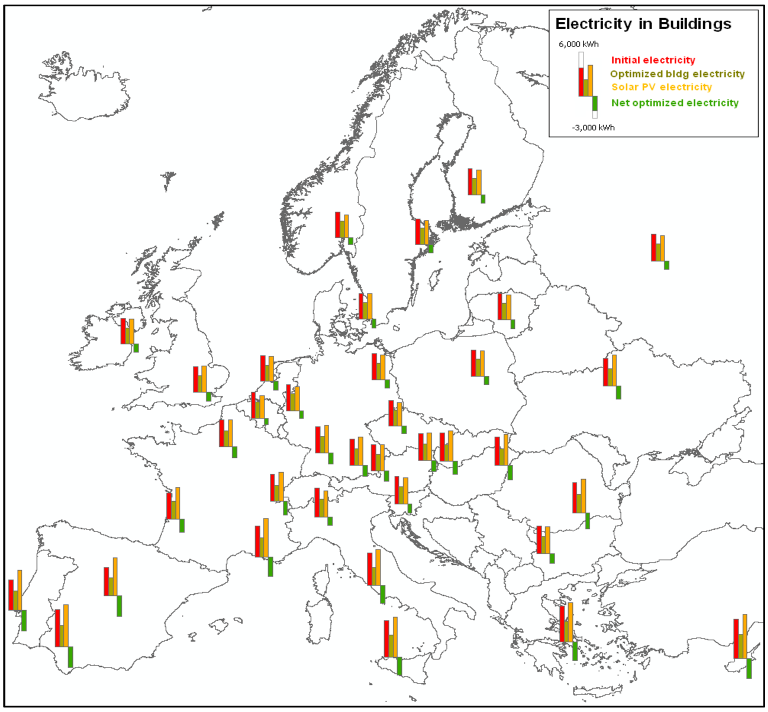

Figure 1 Base building electricity (red) v. optimized building (olive), annual PV power production (orange) and net electricity (green)

The optimization results and option selections reflect climatic realities with much greater insulation levels and air tightness being selected in the colder and cloudier locations. After optimization, the building natural gas consumption is much more similar than it begins (Figure 2).

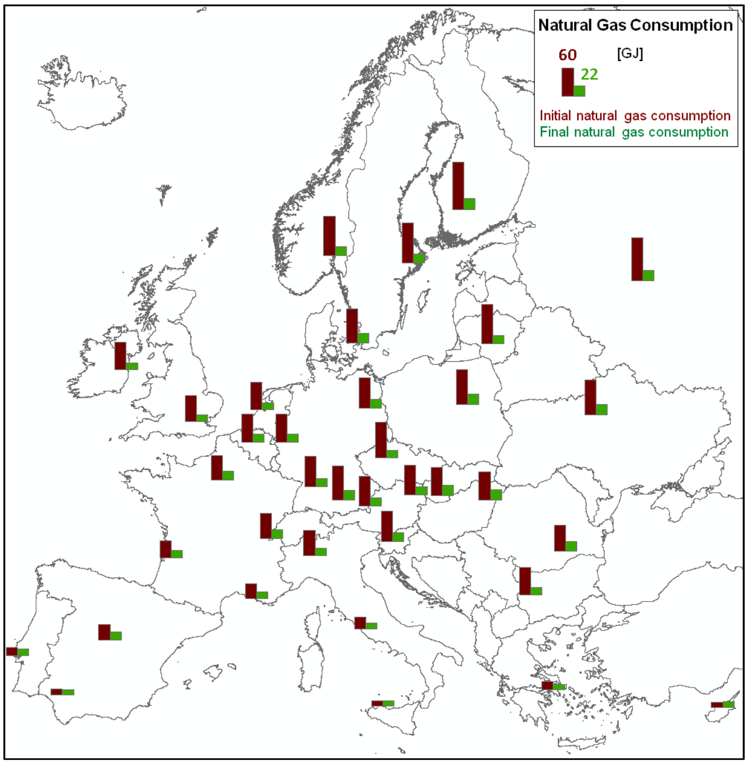

Figure 2: Simulated natural gas consumption before and after the house optimization

The optimization results and the selected options reflect climatic conditions. Much greater insulation levels and air tightness are selected in colder and cloudier locations. It can be seen in Table 4 that after optimization, building natural gas consumption is cut to a low level, particularly for sites in colder climates with elevated heating consumption in the baseline building. It should be noted that including a PV system in the analysis will exclude efficiency measures that are less cost effective than obtaining the same savings from solar systems. If a kWh is produced by this system at a lower cost, the optimization will choose the reduction produced by the PV system rather than by saving that same kWh with an efficiency measure. Low gain windows, light colored tiles, efficient cooling and appliances are important to achieving a positive energy building at low incremental costs. Evaluation for colder locations such as Oslo, Moscow, Tampere and Stockholm showed similar results with very tight construction indicated with very high insulation levels and Passive House type windows.

If we use Feist's proposed Primary Energy Renewable (PER) factor of 2 -- devaluing PV production by 50% to account for load non-coincidence and storage needs -- greater levels of insulation and airtightness will be justified before solar is installed in the optimization [19]. Solar will still be installed, however, since its power production is still needed to reach nearly zero energy.

4.1 Impact of Not Considering Appliances and Lighting in the Optimization

Appliances and lighting are not be included in energy performance assessment according to current legislation. However, our results indicate that this exclusion significantly limits achieved energy savings—particularly for electricity—and it would require an increase of PV production to reach similar energy savings. It should be pointed out that the assumptions done by Passivhaus assumed extremely efficient appliances and very low water heating loads [20], although this fact is sometimes overlooked in considering that standard.

To illustrate the importance of efficient lighting and appliances, we have performed the same optimization analysis of Milan and Lisbon with appliances and lighting not available within the optimization. Results show that achieved energy savings are lower in both locations. For the same building prototype, source energy reductions are lowered from 96% to 86% in Milan, and from 129% to 116% in Lisbon. In particular, the exclusion of lighting and appliances leads to compromised household electricity efficiency. In Milan, this results in a loss of 1466 kWh/year savings.
Although the authors are aware of the fact that some of the lighting and appliances are portable and are difficult to rate and certify with buildings due to installation or changes post occupancy. However, our analysis still points out that achieving these efficiency levels for lighting and appliances remains critical to achieving NZEBs, particularly for reducing electricity consumption. This may require that certification sign off be delayed until after appliances and lighting are installed. The impact of this exclusion can be quantified in little electricity savings (only 141 kWh per year corresponding to 4%). The expensive output of the PV system is partly wasted to cover inefficient appliances: the net reduction in electricity use from adding the PV is reduced by 38%. If there is a larger roof-space, this could be offset by more PV, but at a higher incremental cost. Results also show that considering appliance and lighting is progressively more important in warmer climates where lower internal heat gains can reduce potential space cooling. Generally, we have found that more efficient appliances and light efficiency are cost effective for new residential buildings across MS and different climates. Appliances exclusion also makes the nZEB target more expensive, particularly in colder locations. The additional costs over baseline standard practice to reach 90% and beyond savings increases from 31847 € to 43302 € in Milan. In Lisbon, the costs are nearly the same, but with wider differences in electricity reductions (a loss in electricity savings of 990 kWh/yr).

Our results clearly indicate that including appliance and lighting in the optimization process is important to achieve nearly zero energy buildings at the lowest cost. Moreover, the inclusion of lighting and appliances in the nZEB evaluation will become progressively more important in near future as the use of appliances, plug loads and home electronics is expands in the EU.

5. Conclusions

We describe a comprehensive energy simulation and cost optimization model that is a useful mean to find cost-effectiveness to achieve nearly zero energy buildings. To illustrate results, we provide examples of the calculation method carried out in a new residential building prototype of different climates. We show that it is possible to reach a very low energy design in new buildings with source energy savings approximately between 90% and 100% or beyond. However, the way in which this achievement is accomplished at the lowest cost varies by location.

Whether the optimal path emphasizes or not thermal improvements are strongly dependent on the relative heating load in a given location. The most common approach foresees a combination of good insulation, windows, building tightness as well as Class A++ appliances, lighting, and home energy management systems along with a 4.0 kWp PV system. In each location, the optimized building has less than zero net electricity consumption on an annual basis. Natural gas consumption for space heating and water heating is reduced by 71% in Milan. However, electricity neutrality is only achieved if home lighting and appliances are optimized at the same time that the building "technical" systems are addressed. Efficiency measures are able to cut household appliance electricity by 35% or more in most locations.

Results have shown slightly different optimization results between cold and cloudy locations, such as Brussels, Belgium and sunny ones, such as Lisbon. For instance, in warmer locations, interior appliance efficiency measures are selected earlier as heating loads are not as significantly increased. In case of the warmest locations—cooling loads may be reduced. In colder climates, insulation and building tightness appear much more important.

Finally, we have examined how excluding appliances and lighting from the optimization process, as currently allowed in the 2010/31/EU approach, impact results. We have found such an oversight greatly reduces savings, particularly for electricity, and increases the cost for achieved reductions. Accordingly, we recommend that the optimization process includes lighting and appliances. This inclusion becomes ever more important with future growth in home appliances and electronics grows and associated greenhouse gas emissions.

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Reducing Residential Heating Loads Using Energy Star Windows

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BC Hydro and Research 4 Result

Abstract

Windows represent a major source of unwanted heat loss and heat gain in residential dwellings. Energy Star windows can substantially reduce windows-related HVAC loads while increasing resident comfort. The purpose of this study was to conduct a process, market and impact evaluation of the residential Energy Star windows program conducted by BC Hydro in British Columbia, Canada, which provided rebates covering both residential new construction and retrofits. Given the range of issues examined in the evaluation, the study employed multiple lines of evidence and multiple analysis methods. Data sources included pre-program market research, trade ally interviews, survey of some 800 customers who purchased windows, and on-site audits. Data analysis included tabulation of survey data responses, structural equation modeling of the demand and supply sides of the windows market, and energy modeling, using RESFEN, a DOE 2.1 based simulation software with a user-friendly interface.

Introduction

Increasing energy efficiency and reducing energy consumption is viewed by some researchers as a cost effective means of reducing energy sector carbon dioxide and other greenhouse gas emissions which are implicated in global warming ([10], [18], [19], [21]). In response to concerns that market barriers and market failures lead to sub-optimal levels of investment in energy efficiency, a number of policy instruments have been proposed ([6], [7]. [9], [11]-[14], [17]). Non-market based policy instruments include regulation through building codes and minimum energy performance standards. Market based policy instruments include white certificates, carbon taxes, cap and trade systems, and voluntary standards and labeling. Voluntary standards and labelling are complementary market-based instruments which have been promoted as a cost-effective means of increasing energy efficiency. The Energy Star program develops and promotes standards and labelling for energy efficient products, such as energy efficient windows ([2], [5]).

Many utilities in North America are promoting energy efficient building shell measures to: (1) respond to directives from utility regulators that all cost effective energy conservation measures be pursued; (2) postpone costly generation, transmission and distribution investments; (3) maintain reliability by reducing peak demand; (4) provide value to their customers; and (5) reduce greenhouse gas emissions. A number of studies have focussed either in whole or in part on energy efficient windows, including the impact of energy efficient windows on energy loads. Some of these studies have considered energy requirements for space heating and cooling and the efficiency with which these loads are met. These studies have found find that the key drivers of space heating and cooling loads are: (1) thermal bridging through ground contact, the opaque envelope, and the windows; (2) infiltration of outside air; (3) external temperature; (4) solar radiation absorption and reflection; (5) set-point temperature, set-back temperature and internal gains; and (6) occupancy. Analysis in the applied work is typically based on either bin-type models such as HOT-2000 or on hourly simulation-type models such as DOE 2.1 or RESFEN. These models are used primarily to model space conditioning loads (heating, cooling) as well as the interaction between space conditioning loads and ancillary heat sources such as lighting and appliances. Simple engineering algorithms based on survey information are used to model secondary loads including water heating, ventilation, lighting, refrigeration and plug loads as inputs to these simulation models ([1], [3], [4], [8], [15], [16] [20]).

This study evaluates BC Hydro’s Energy Star Windows program, and it makes three main contributions. First, it is one of the few studies to comprehensively examine the demand-side and the supply-side of the residential windows market. Second, it uses detailed on-site and survey information to accurately model unit energy savings using appropriately engineering software. Third, it applies detailed time-series modelling to determine incremental installation of Energy Star windows for both the new construction and the retrofit windows markets.

Program Background

Space heating makes up about thirty percent of a typical home's energy bill in British Columbia, and windows are the most important source of heat loss in many residential dwellings. BC Hydro has had a series of initiatives aimed at encouraging the installation of energy efficient windows in new dwellings and as replacement windows. In 1989, BC Hydro initiated the comprehensive Home Improvements Program. This program included detailed on-site energy audits combined with free and co-funded energy conservation measures including low flow shower heads, faucet aerators, draft proofing, insulation and energy efficient windows. Although the program had good market take-up, it proved to have poor cost effectiveness given available energy efficient windows. The replacement programs were the Renovation Rebate Program (October 2003 to March 2005) and the Power Smart New Home Program (October 2002 to June 2005). These programs respectively offered developer and home owner incentives for upgraded insulation and low-emissivity, argon filled windows, but the take-up for both of these programs was low as they were limited to electrically heated dwellings, and excluded the much larger gas heated residential market. To overcome the limitation of small potential market, these two programs were replaced by the Power Smart Renovation and New Home Windows Initiative programs. This study provides an evaluation of this program from April 1, 2007 through March 31, 2009.

Energy Star is an international symbol for products that are among the most efficient available in the market. Only products which meet the relevant Energy Star criteria and have been subjected to rigorous testing and certification are permitted to use the Energy Star label on their products. In Canada, the Office of Energy Efficiency of Natural Resources Canada regulates certification of Energy Star windows. The Energy Star window standard was introduced in April 2004. To qualify as an Energy Star window, the window must meet the maximum allowable U-value, which varies by climate zone. The U-value refers to the watt loss per degree Celsius per square metre of glazing. Canada is divided into four climate zones where zone A is the mildest zone and zone D is the coldest zone, and only zones A, B and C are represented in British Columbia. Table 1 shows the maximum watt loss for Energy Star windows as well as the baseline windows. The baseline window is a double glazed window with clear glass, vinyl frame and sash, air filled, with a U-value of 2.73. The baseline window watt loss is based on pre-program market research with manufacturers and distributors. To meet the Energy Star requirements, windows will need to have some combination of the following features: double or triple glazing with a sealed glass unit; low-emissivity glass; an inert gas such as argon or krypton in the sealed unit; low conductivity of warm edge spacer bars; insulated frame; and good air tightness. Low-emissivity refers to a layer which goes between the glass panes and which slows the transfer of heat between the inside and outside of the window and reflects sunlight reducing heat gain in the summer time.

Table 1. Energy Star and Baseline Windows U-values

Climate Zone	Energy Star Windows (W per m^2 per °C)	Baseline Windows (W per m^2 per °C)
A	2.00	2.73
B	1.80	2.73
C	1.60	2.73

Data and Method

For this study, there were five main activities or issues: (1) conduct a program review; (2) undertake a supply-side assessment; (3) undertake a demand-side assessment; (4) estimate sales impacts for Energy Star-qualifying windows; and (5) estimate energy and peak savings. We used a multiple lines of evidence approach, since no single line of evidence provided information on all of the evaluation activities or issues.

Program Review. To conduct the program review and develop the program logic model, we reviewed program documents, interviewed BC Hydro program staff, and conducted a literature review focussing on recent studies and reports of residential windows. The purpose of the literature review was to understand the issues, data sources, methodologies, conclusions and lessons learned from previous research on energy efficient windows programs. Most of the studies available were baseline and tracking studies rather than impact studies, but they still provided useful insights to help plan the scope and methods for the present study.

Supply-side Assessment. To undertake the supply-side assessment, we conducted three detailed trade ally surveys. The purpose of the trade ally surveys was to collect manufacturer, wholesaler and retailer views on the nature of and changes in the windows market, including market size, Energy Star qualifying share, and prices for Energy Star qualifying and non-qualifying windows.

Demand-side Assessment. To undertake the demand-side assessment we conducted a single detailed customer survey. The purpose of the participant survey was to collect information on program participant reasons for replacing the windows, decision factors on choice of windows, customer satisfaction with the windows purchased, and non-energy benefits. A telephone survey was used where the sampling frame was customers who received a rebate through the previous windows program. The sample size for this survey was 800, which was larger than the usual sample required because of the need to disaggregate by electricity and natural gas as the main space heating fuel.

Sales Impact. To estimate the sales impact of the program, we built a detailed market model using econometric analysis. The purpose of the econometric analysis was to estimate the impact of the program during F2008 and F2009 on sales of Energy Star qualifying windows. This was undertaken separately for the new home market segment and the retrofit market segment. Annual data for the period F1998-F2009 was used, where a fiscal year runs from April 1 of a given year to March 31 of the following year.

Energy and Peak Savings. To estimate energy and demand savings, we used engineering simulations. The purpose of the engineering analysis was to estimate the impacts of the program on electricity energy consumption, electricity peak consumption, natural gas energy consumption and natural gas peak day consumption. The analysis was based on whole dwelling simulations using the RESFEN computer model.

Results

Program Review

The Pre-program launch research found four main barriers to the increased installation of Energy Star windows. (1) Affordability. The additional capital costs of Energy Star windows directly competed against other, more visible window features. These additional capital costs reduced the penetration of Energy Star windows in the market. (2) Awareness. Many consumers were not aware of what product features constitute an Energy Star window. Many consumers believed that double glazed windows were energy efficient and were not aware of the reduced energy costs associated with Energy Star windows. (3) Accessibility. The Energy Star windows standard was relatively new, and although many manufacturers had the technology to manufacturer Energy Star windows, the number of available models was small and premium priced. (4) Availability. Energy Star windows were available in a limited range of models and sold in a small number of establishments. The program addressed these barriers through four main activities.

Window Certification Support. BC Hydro partnered with the BC Ministry of Energy, Mines and Petroleum Resources to provide funding to manufacturers for Energy Star certification testing and for modelling simulations to support manufacturer applications for Energy Star certification. BC Hydro underwrote fifty percent of the cost of certification up to a maximum of $10,000. The outcome of this activity was an increased range of Energy Star qualifying windows available for purchase in British Columbia.

Manufacturer and Retailer Support. BC Hydro undertook a variety of activities to provide education and training for trade allies on the advantages and benefits of Energy Star windows. The majority of this activity was through face-to-face discussions supported by sales kits. The outcome of this activity was trade ally staff trained and appropriate materials made available to trade allies.

Advertising and Other Promotions. BC Hydro had previously undertaken extensive promotion of the Energy Star label, so that it was possible to leverage both this awareness of the Energy Star brand and consumer awareness of the advantages and benefits of energy efficient windows for the current windows promotions. Specific sub-activities included mass advertising to raise customer awareness and drive customers to the BC Hydro website or to the call centre for further information, cooperative advertising with manufacturers, point of purchase materials and contests. The outcome of this activity was increased customer interest and familiarity with Energy Star windows.

Manufacturer and Provincial Windows Incentive. In earlier BC Hydro window programs, BC Hydro co-funded incentives of the purchase of energy efficient windows. In this program, BC Hydro worked with manufacturers to encourage them to offer their own incentives, and this price break was reinforced due to BC Hydro's efforts which led to the elimination of the 7% provincial sales tax on Energy Star windows. The outcome of this activity was reduced customer first costs for Energy Star qualifying windows. This improved the potential pay-back period for those installing Energy Star windows.

Table 2 provides a summary program logic model for the Power Smart Renovation Rebate and New Home Windows Initiative, which is based on the program activities outlined above. For each of the four sets of activities, the summary logic model documents the chain from inputs to outputs to purposes to goals. In other words, the model says that at each level of the logic if the assumptions are met, then the next level of the logic will be achieved. Our assessment is that each of the logic chains is plausible and realistic. We therefore conclude that the program has a valid and realistic program rationale.

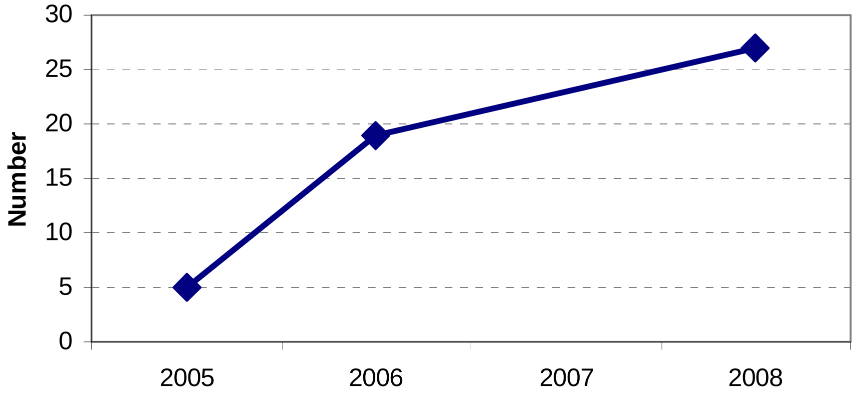
Table 2. Program Logic Model

	Window Certification Support	Manufacturer and Retailer Support	Promotion	Manufacturer and Provincial Window Incentive
Inputs	BC Hydro/ Government co-funding for window testing and certification	Sales materials prepared and distributed and sales staff training available	Promotion and website support for Energy Star windows	Manufacturers provide incentives for Energy Star qualifying windows, BC eliminates 7% tax
Outputs	Increased range of Energy Star qualifying windows available	Trade ally staff trained and appropriate materials made available	Increased customer awareness/ knowledge of Energy Star windows	Reduced customer first costs for Energy Star qualifying windows
Purpose	Increased supply of Energy Star qualifying windows in British Columbia		Increased demand for Energy Star qualifying windows in British Columbia	
Goals	1. Increased Energy Star qualifying window sales 2. Reduced electricity consumption and peak 3. Reduced natural gas consumption and peak			

Supply-Side Assessment

Table 3 presents the number of window manufacturers producing Energy Star windows in British Columbia. The number of window manufacturers producing Energy Star windows in British Columbia increased from 5 in June 2005 to 19 in September 2008 and to 27 in May 2008.

Figure 3: British Columbia Manufacturers of Energy Star Windows



Window manufacturers were asked a variety of questions about their levels of satisfaction with Energy Star windows and the windows program. Table 4 summarizes the percentage shares of those who were either satisfied or very satisfied as well as their average satisfaction scores on a 5-point scale were 1 is not at all satisfied and 5 is very satisfied. The share of manufacturers who were either satisfied or very satisfied with various attributes is as follows: overall program satisfaction (50%); frequency of communications form BC Hydro (50%); display and promotional materials provided by BC Hydro (50%); opportunities for co-operative joint advertising with BC Hydro (39%); processes and procedures to certify windows as Energy Star windows (39%); effectiveness of BC Hydro's education awareness campaign (28%); and BC Hydro's sales training in Energy Star windows (17%).

Table 4. Manufacturer Satisfaction

	Satisfied (% choosing 4 or 5)	Satisfaction score (average)
Overall program satisfaction	50	3.1
Frequency of communications from BC Hydro	50	3.4
Display and promotional materials provided by BC Hydro	50	3.3
Opportunities for co-operative/joint advertising with BC Hydro	39	3.3
Processes and procedures to certify window as Energy Star	39	3.2
Effectiveness of BC Hydro's education/awareness campaigns	28	3.1
BC Hydro's sales training on Energy Star windows	17	2.4

Demand-Side Assessment

Customers were asked a variety of questions about their levels of satisfaction with Energy Star windows and the windows program. Table 6 summarizes the percentage shares of those who were either satisfied or very satisfied as well as their average satisfaction scores on a 5-point scale were 1 is not at all satisfied and is very satisfied. The share of customers who were either satisfied or very satisfied with various attributes is as follows: overall satisfaction with the Energy Star windows program (68%); knowledge of the window contractor (79%); choice of windows qualifying for the rebate (70%); information available on the Energy Star windows program (66%); information available on Energy Star windows (69%); and satisfaction with Energy Star windows (95%).

Table 5. Customer Satisfaction

	Satisfied (% choosing 4 or 5)	Satisfaction score (average)
Overall satisfaction with the Energy Star windows program	68	3.9
Knowledge of the window contractor	79	4.4
Choice of windows qualifying for the rebate	70	4.2
Information available on the Energy Star windows program	66	4.0
Information available on Energy Star windows	69	4.0
Satisfaction with Energy Star windows	95	4.6

Customers were asked about the primary reason for replacing their windows. Table 6 shows the percentage share for the main responses that they provided. The primary reasons for replacing windows included: save energy/money (30%); improve comfort/reduce drafts (16%); windows were old (13%); moisture/condensation (10%); remodelling/renovating (5%); windows broken (4%); other (10%); don't know/refused (10%).

Table 6. Primary Reason for Replacing Windows

Reason	Share (%)
Save energy/money	30
Improve comfort/reduce drafts	16
Windows were old	13
Moisture/condensation	10
Remodelling/renovating	5
Windows broken	4
Other	10
Don't know/refused	10
Total	100

Sales Impacts

We applied a simple demand and supply model in which the price is established to clear the market, that is, the quantity demanded equals the quantity supplied at the market clearing price. Microeconomic theory suggests that the demand for a product depends primarily on three factors: an activity variable such as income or output; a price variable such as the unit price for the product; and the prices of a substitute product such as the unit price of the substitute. Often the ratio of the own price to the substitute price is used as the price variable, and we do so here. We assume below a linear demand function for Energy Star windows where the quantity variable is the area of glazing in thousands of square feet, the activity variable is the number of housing starts in thousands, and the price variable is the ratio of Energy Star price per square foot of glazing to non-Energy Star price per square foot of glazing. We use information for the twelve-year period from F1998 to F2009. For the earlier years in the period, the Energy Star specification was not developed, so we use as a proxy windows that at a minimum were low emissivity and thermally broken.

Table 7 shows the results of the demand side regression modelling. The results for each equation are shown in a column and the results for each variable are shown in a row. The standard deviations for each parameter estimate, the significance for the F-test, and the estimated auto-correlation for the Durbin-Watson test are shown in parentheses. One, two, or three asterisks indicate that the coefficient is statistically significant at the 10%, 5% or 1% level respectively. Equation (1) has an excellent fit, with an adjusted R-squared value of 0.97, and all of the regression coefficients are statistically significant. The equation says that for glazing in new residential construction, an increase of 1,000 housing starts increases Energy Star glazing area by 34,300 square feet, a doubling of the Energy Star to non-Energy Star price ratio reduces Energy Star glazing area by 179,000 square feet, and the presence of the Power Smart windows program increases the Energy Star glazing area by 1,720,000 square feet in the first program year (F2008) and by 3,440,000 square feet in the second program year (F2009). Equation (2) has an excellent fit, with an adjusted R-squared value of 0.99, and all of the regression coefficients are statistically significant. The equation says that for glazing in renovations, an increase of 1,000 housing starts increases Energy Star glazing area by 10,000 square feet, a doubling of the Energy Star to non-Energy Star price ratio reduces Energy Star glazing area by 58,000 square feet, and the presence of the Power Smart windows program increases the Energy Star glazing area by 721,000 square feet in F2008 and by 1,442,000 square feet in F2009. Equation (3) has an excellent fit, with an adjusted R-squared value of 0.98, and all of the regression coefficients are statistically significant. The equation says that for glazing in new residential construction and retrofits, an increase of 1,000 housing starts increases Energy Star glazing area by 44,300 square feet, a doubling of the Energy Star to non-Energy Star price ratio reduces Energy Star glazing area by 237,000 square feet, and the presence of the Power Smart windows program increases the Energy Star glazing area by 2,440,000 square feet in F2008 and by 4,880,000 square feet in F2009.

Table 7. Determinants of Energy Star Glazing Area (000 square feet)

	New Construction (1)	**Renovation (2)**	**Total (3)**
Constant	21,296*** (4872)	7385*** (736)	28,680*** (4,819)
Starts (000)	34.3*** (12.0)	10.0*** (3.2)	44.3*** (12.9)
Price ratio	-179*** (40)	-58*** (5.8)	-237*** (40)
Program	1,720** (719)	721*** (86)	2,440*** (734)
Adjusted R^2	0.97	0.99	0.98
F	114.6 (0.00)	316.7 (0.00)	182.6 (0.00)
Durbin-Watson	2.43 (-0.21)	2.03 (-0.01)	2.57 (-0.28)

Note. One, two or three asterisks means that the coefficient is statistically significant at the 10%, 5% or 1% level respectively.

The results for the estimated supply curve are shown in Table 8. Equation (4) has a good fit, with an adjusted R-squared value of 0.72, with two of the three coefficients statistically significant. In particular, the coefficient on the program variable is not statistically significant which means that the current program has no independent impact on price. The key message from this equation is that the price of Energy Star windows falls by 2.2% per year.

Table 8. Determinants of Energy Star Price Ratio (ES price/non-ES price)

	Price **(4)**
Constant	1.26*** (0.039)
Trend	-0.022*** (0.0077)
Program	-0.051 (0.055)
Adjusted R^2	0.72
F	12.7 (0.00)
Durbin-Watson	1.16 (0.42)

Note. One, two or three asterisks means that the coefficient is statistically significant at the 10%, 5% or 1% level respectively.

Energy and Demand Savings

Six basic scenarios were modeled depending on foundation type and number of stories in the dwelling. The six scenarios were: (1) slab on grade, 1 story; (2) slab on grade, 2 story; (3) crawl space, 1 story; (4) crawl space, 2 story; (5) basement, 1 story; and (6) basement, 2 story. The six basic scenarios were modelled for electricity and natural space heating fuels and for each of the three climate zones for a total of thirty-six scenarios. Table 9 summarizes unit energy savings results. Note that the base for electricity savings is 100% of glazing, since all dwellings have electricity, but the base for natural gas savings is 84% of glazing, because 84% of dwellings have natural gas or other as the main space heating fuel.

Table 9. Unit Energy Savings

Heating Type	Energy Star Zone A	Energy Star Zone B	Energy Star Zone C	All Zone Average
Annual electricity savings per square foot of window (kWh/square foot)				
Electric resistance heating	5.286	10.138	14.579	6.144
Gas furnace heating	0.171	0.324	0.466	0.216
Average electric	2.237	2.580	6.591	2.717
Annual natural gas savings per square foot of window (GJ/square foot)				
Gas furnace	0.0246	0.0466	0.0671	0.0311

Table 10 presents the estimated total savings results. These estimated savings were as follows: (1) electricity energy savings 6.6 GWh for first year and 13.3 GWh for second year; (2) electricity demand savings 1.4 MW for first year and 0.9 MW for second year; (3) gas energy savings 75.9 TJ for first year and 151.8 TJ for second year; (4) gas demand savings 393.9 GJ per day for first year and 785.8 GJ per day for second year.

Table 10. Energy and Peak Savings

Electricity		GWh per year	MW per peak day
New	F2008	4.7	0.9
Reno	F2008	1.9	0.5
Total	F2008	6.6	1.4
New	F2009	9.4	2.0
Reno	F2009	3.9	0.9
Total	F2009	13.3	2.9
Gas		**TJ per year**	**GJ per peak day**
New	F2008	53.5	277.0
Reno	F2008	22.4	115.9
Total	F2008	75.9	392.9
New	F2009	107.0	553.9
Ren	F2009	44.8	231.9
Total	F2009	151.8	785.8

Conclusions

The study has five main conclusions. First, based on detailed interviews with stakeholders and a review of program documents and files, four main program activities were identified and examined in detail to develop a detailed shared understanding of how the program worked. These included: (1) Window Certification Support; (2) Manufacturer and Retailer Support; (3) Advertising and Other Promotions; and (4) Manufacturer and Provincial Windows Incentive. A valid and robust summary logic model documents the chain from inputs to outputs to purpose to goals, and this demonstrates that the program rationale is sound.

Second, customers were asked the relative importance of various attributes in their choice of windows. . The primary reasons for replacing windows included: save energy/money (30%); improve comfort/reduce drafts (16%); windows were old (13%); moisture/condensation (10%); remodelling/renovating (5%); and windows broken (4%). Customers were also asked a variety of questions about their levels of satisfaction with Energy Star windows and BC Hydro's windows program. The share of customers who were either satisfied or very satisfied with various attributes is as follows: overall satisfaction with the Energy Star windows program (68%); knowledge of the window contractor (79%); choice of windows qualifying for the rebate (70%); information available on the Energy Star windows program (66%); information available on Energy Star windows (69%); and satisfaction with Energy Star windows (95%).

Third, manufacturers were asked about their satisfaction with the program. The share of manufacturers who were either satisfied or very satisfied with various attributes is as follows: overall program satisfaction (50%); frequency of communications form BC Hydro (50%); display and promotional materials provided by BC Hydro (50%); opportunities for co-operative joint advertising with BC Hydro (39%); processes and procedures to certify windows as Energy Star windows (39%); effectiveness of BC Hydro's education awareness campaign (28%); and BC Hydro's sales training in Energy Star windows (17%).

Fourth, we built a two equation market model of the residential windows market. The key demand side finding is that the Power Smart windows program increased the Energy Star glazing area by 2,440,000 sq. ft. in the first program year and by 4,880,000 square feet in the second program year. The key supply side finding is that the Energy Star windows prices fall by about 2.2% per year.

Fifth, we estimated energy and demand savings using engineering algorithms and RESFEN simulation software. These estimated savings were as follows: (1) electricity energy savings 6.6 GWh for first year and 13.3 GWh for second year; (2) electricity demand savings 1.4 MW for first year and 0.9 MW for second year; (3) gas energy savings 75.9 TJ for first year and 151.8 TJ for second year; (4) gas demand savings 393.9 GJ per day for first year and 785.8 GJ per day for second year.

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Dynamic Methodology for the Evaluation of Occupant Behaviour and Residential Energy Consumption.

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Abstract

Careful examination of energy consumption in the building sector, which is about 38% of the final energy consumption in EU-27 (Eurostat data 2011) is needed in order to identify the specific areas for energy savings. Due to improved insulation levels of buildings this saving potential moves to more dynamic energy use sectors such as gains from appliances, high energy demand patterns (such as from heat pump) and consumer behaviour.
Increasing interest in research in energy technologies result into rapid transformation of a sustainable and secure energy future for Europe. Together with further advancements in information technology, such as internet, it heralds many opportunities for European research, building construction and appliance industry. The development of high energy performance buildings, in which ICT will be fully integrated in the energy system, requires the application of dynamic methods, in conjunction with occupant behaviour models, in order to make use of the available energy resources with highest efficiency for a sustained living and working environment.

At present, the EU residential building stock consumes about 2/3 of the energy mainly for space heating and cooling, while the remaining 1/3 (electricity) is consumed by appliances and light. The recast of the Energy Performance for Buildings Directive (EPBD) (2010/31/EU) requests for nearly-zero energy buildings (nZEB) that can be fulfilled when overall building energy performance is improved, renewable energy systems are installed and storage technology is applied. It is already anticipated that the current electricity grid cannot manage this unless proper information and computation technology is put in place. The EPBD fixes the reduction of the space heating and cooling, ventilation, lighting and domestic hot water energy consumption of buildings. However the electronic appliances and other electrical devices are excluded from these requirements. It is then envisaged that these electrical loads will have a higher contribution, in percentage, within the overall energy consumption of these high energy performance buildings. Since the electrical loads are characterized for being highly user dependent and stochastic by definition, this will add more complexity to the analysis and prediction of the overall energy loads of the high energy performance buildings.

In this context, a combination of statistical and dynamic evaluation methods, are techniques that must be used to analyse time series of data related to dynamic processes and to identify occupant behaviour and typical parameters of the physical processes for evaluation. Data from smart meters are typical examples of such time series and provides details of energy usage patterns. By using dynamic evaluation techniques (system identification) dynamic effects due to accumulation of energy (heat and electricity) in the building interior construction, envelope and equipment are properly taken into account, which combined with the occupant behaviour, provides the overall vision necessary to model the residential thermal and power demand.
Software techniques using dynamic calculation rules and occupant behaviour models can turn smart metering into more intelligent environments. To clarify the difference between smart and intelligent metering environments the following brief definitions can be applied: smart meters are, compared to traditional electricity, water or gas meters, taking readings in more and regular detail and communicate them electronically through some network to the utility (and end-user) for monitoring and billing purposes (often referred as automated meter reading). Intelligent metering environments can in addition, analyse these observations, identify characteristics and make decisions aiming to improve further the optimization of energy efficiency. This may be the near future when these modern, wireless devices come closer to the end-user, the consumer of energy so to say. Utility and end-user

can benefit from this information. This paper presents a statistical method for modelling the behaviour of household occupants and sets out the basis for estimating the overall residential energy consumption using dynamic evaluation techniques.

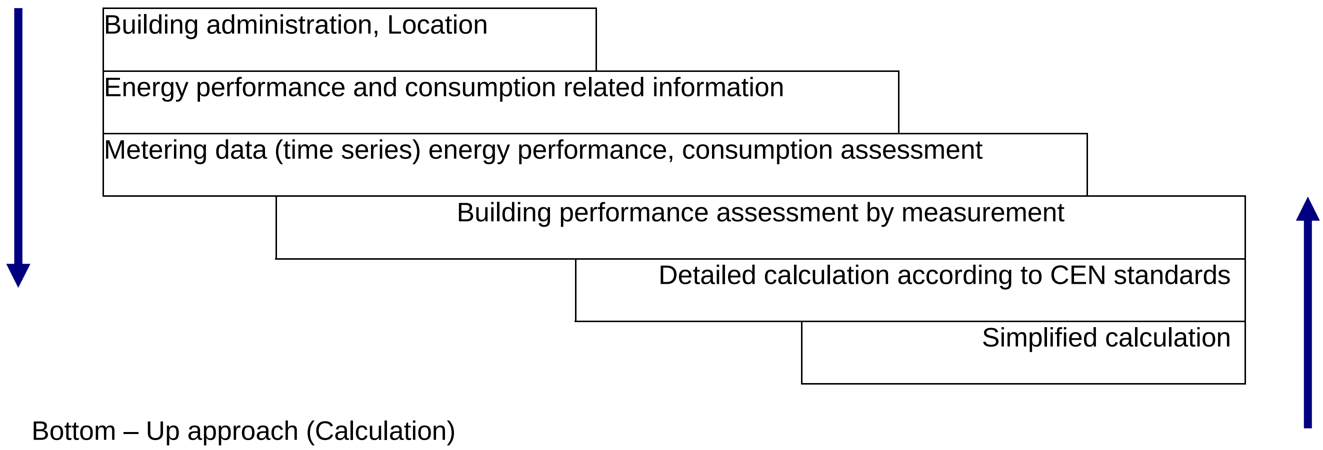
Introduction

The Directive on the Energy Performance of Buildings introduces a general framework for a methodology to calculate the energy performance of buildings. On the other side, the ICT sector can deliver tools that are vitally needed to collect, process, and manage the data and present it in a standardized format. With the rolling out of advanced metering in the residential sector the importance of time series analysis becomes evident. The approach for assessing information contained in these regular and more frequent readings is by means of application of sophisticated mathematical and statistical techniques. To assess from limited but at the same time informative observations from the metering equipment, the energy performance of the building as well as the energy consumption by the occupants can be obtained.

In general it can be noted that the more insulated the building envelope is the more important becomes the variability from user behaviour and the use of energy consuming appliances that is reflected in thermal gains. Within that context it is important to consider the differences between the expressions energy performance, energy efficiency and energy consumption. An assessment of the energy performance of a building can be performed in different ways. In the schematic representation below is given a top-down approach, starting from administrative building data. A bottom-up approach starts from the calculation method as presented by the CEN standards, related to the EPB Directive and hence minimum requirements set by the individual Member States

Table 1.

Top – Down approach (empirical – databases, metering)



Bottom – Up approach (Calculation)

In relation to this assessment one should consider the time aspect, e.g. the impact of time related aspects of different energy related processes. This includes hourly, daily, monthly or seasonal and yearly approaches of the overall performance assessment.

- Hourly : light, ventilation, occupant behaviour
- Daily: solar gains, weather dependence, window-opening, gains, ventilation
- Monthly: seasonal: solar gains, wind, temperature, functionality, system performance issues
- Yearly: solar gains, temperature.

The consequences for the assessment are evident in particular when the uncertainty of the assessed performance value is taken into account. Energy labelling is in most cases performed by auditors who examine drawings, climate and other building administration, that may include age of the building, local requirements for insulation and ventilation, which may result in different label resulting values for the same object.

An important step in the proposed method is to split from the available data those that are correlated with the fabric (thermal characteristic of the building) and those that are occupant dependent. In addition the available data may be split for seasonal related aspects, like the heating and cooling period. Prior knowledge is in all cases is very helpful in the analysis process.

Proposed method.

The aim of the herewith presented method is to derive from available metering data and climate data the amount of energy that is needed by the building to fulfil the minimum requirements for the type of building, e.g. for residential dwellings a design indoor temperature of for example 20°C. This energy need would correspond with the performance of the construction in a typical climate while the energy consumed by the occupants, their appliances and behaviour (like different indoor temperature setting) would result in the remaining part of the energy readings. See figure 1 for further explanation.
The proposed method therefore has to be able to distinguish between the building energy needs and the occupants' energy consumption. One way to separate building energy needs and occupant consumption is to classify occupant behaviour through Hidden Markov Models (HMM). The occupant behaviour is classified based on the electricity consumption, implying that only indirect measurements are used in the classification. Electricity can be considered as the most important energy carrier linked to non-EPB use of energy.

Building energy performance and consumption assessment.

According to the EPBD the performance of the building deals with energy needed for heating, cooling, ventilation, hot water and light (for non-residential buildings), referred to as EPB use. These building energy needs are strongly related to the climate, in particular the ambient temperature, the solar radiation and the impact of wind. In general, the major part of energy consumption is required for the building energy needs.
The trick is to correlate EPB use of energy to climate and fabric parameters and to correlate non-EPB use to the user of the building. The latter includes energy consumed by appliances and the pattern of usage by the occupants. The variation depends a lot on how many appliances and people are living or working in the building comprising when energy is used. High frequency readings of electricity consumption facilitate the assessment of this information. Readings of water, heat and gas or other carriers would make the assessment even more informative.

Gathered from building administration is knowledge about the exact location and the nearest weather station for reliable climate data. Which fuel is used and what data is available, like interval, unit but also for which purpose (like gas for heating, cooking, hot water).

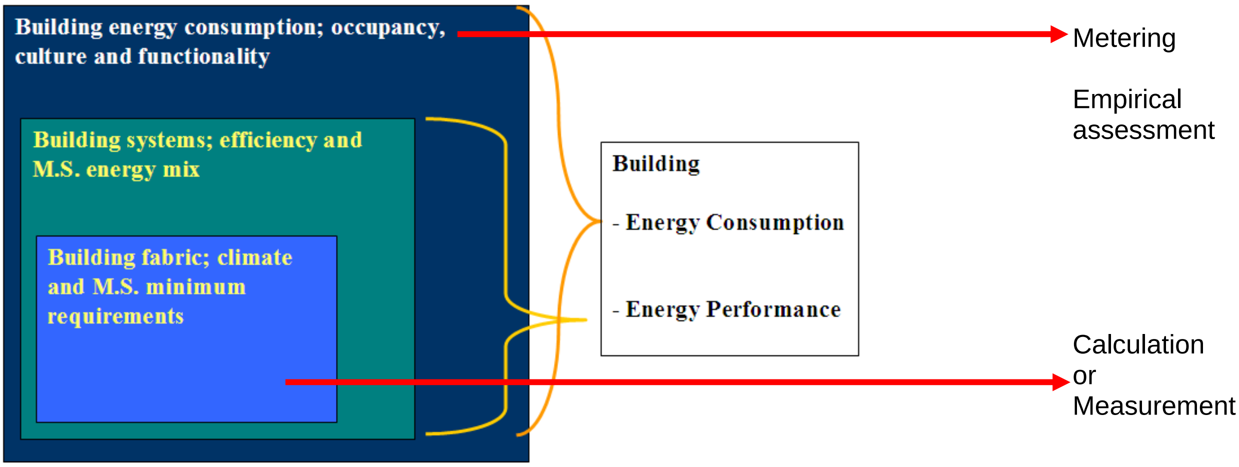


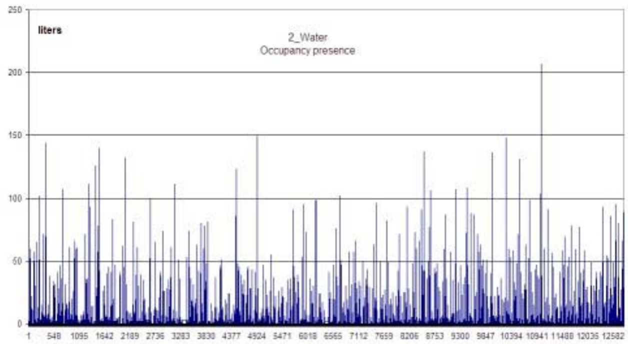
Figure 1. Relation between energy performance and energy consumption

Case study

Hourly metering data has been made available to study the feasibility of the fore mentioned method. The data covers a period of well over a full year and hence includes all seasons. The building contains 44 apartments for which 38 have been selected for analysis. Data is also hourly for the important climate variables, temperature, solar radiation, wind, humidity are from a nearby weather station. This case study will deal with the energy needed for electrical appliances, lighting and in very few dwellings, for space cooling.

Description of the building.

The concerned building is a five floor apartment block with 4 separate entrances. The smallest dwelling is 40 m^2 while the biggest is 67 m^2. The building has a centralized system to provide the thermal needs for domestic hot water and space heating. This system is formed by two central boilers and a solar thermal system formed by 55 solar thermal panels placed on the roof of the building. The hot water is distributed to the flats through a vertical tube ring where individual instant heat exchangers are connected. The occupancy varies from 1 person to 5 while during the year presence of people is not evident.



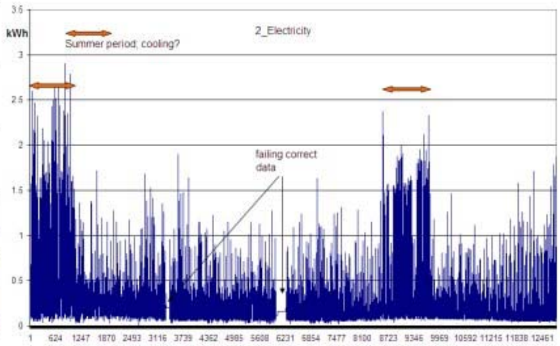


Figure 2. Water consumption **Figure 3. Electricity consumption**

Available input data

For each apartment the following variables are available: domestic hot water, space heating, electricity and water and in addition the indoor air temperature. In 6 flats, an electrical sub-metering which accounts for the electricity for cooking and for lighting, is also available. Note that all apartments have electric cooking available and possess a fridge and television.

From hourly electrical consumption data, the presence of occupancy can be derived in order to select a period for further analysis. Figures 2 to 5 give an impression of the hourly data for a period of 18 months that is available.

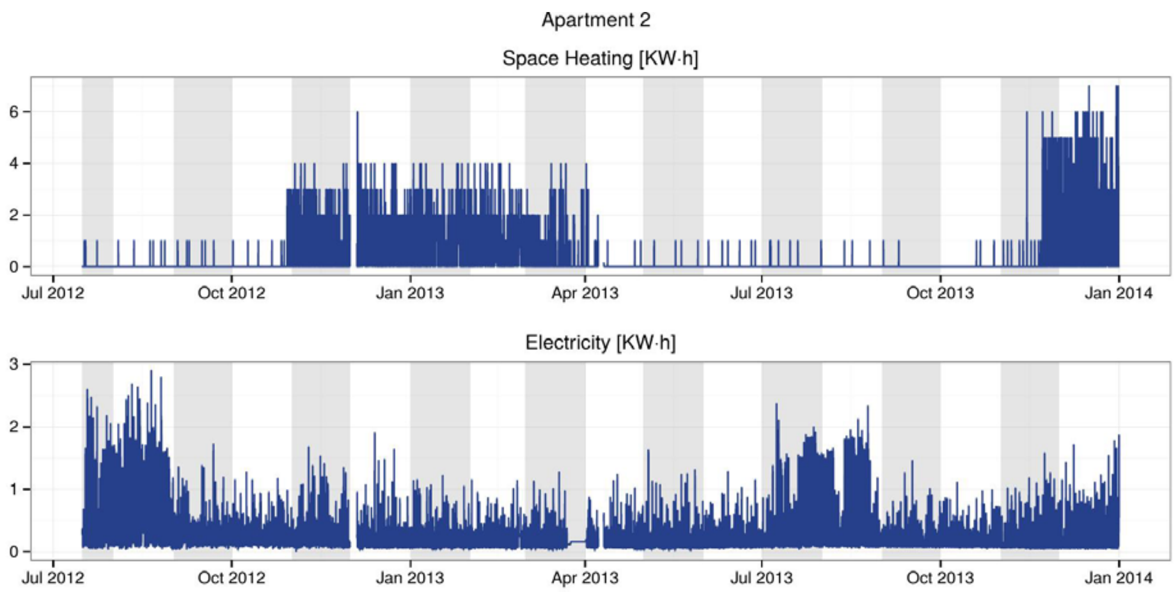


Figure 4. Space heating consumption and electricity consumption of apartment 2

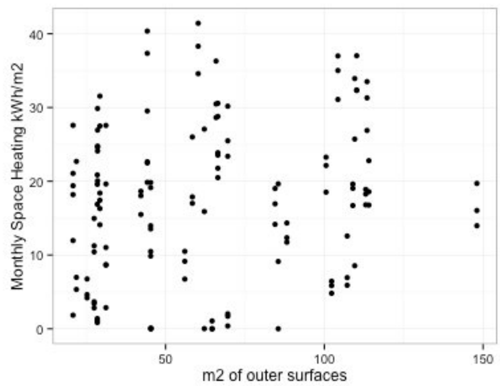


Figure 6. Space heating consumption

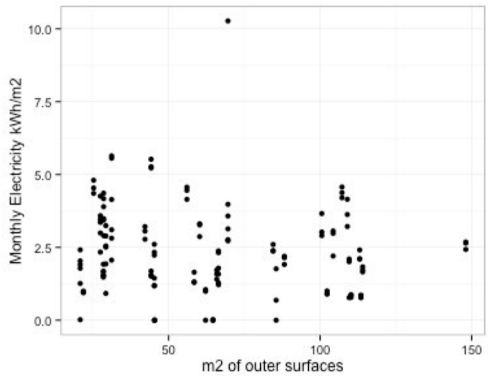


Figure 7. Hot water consumption

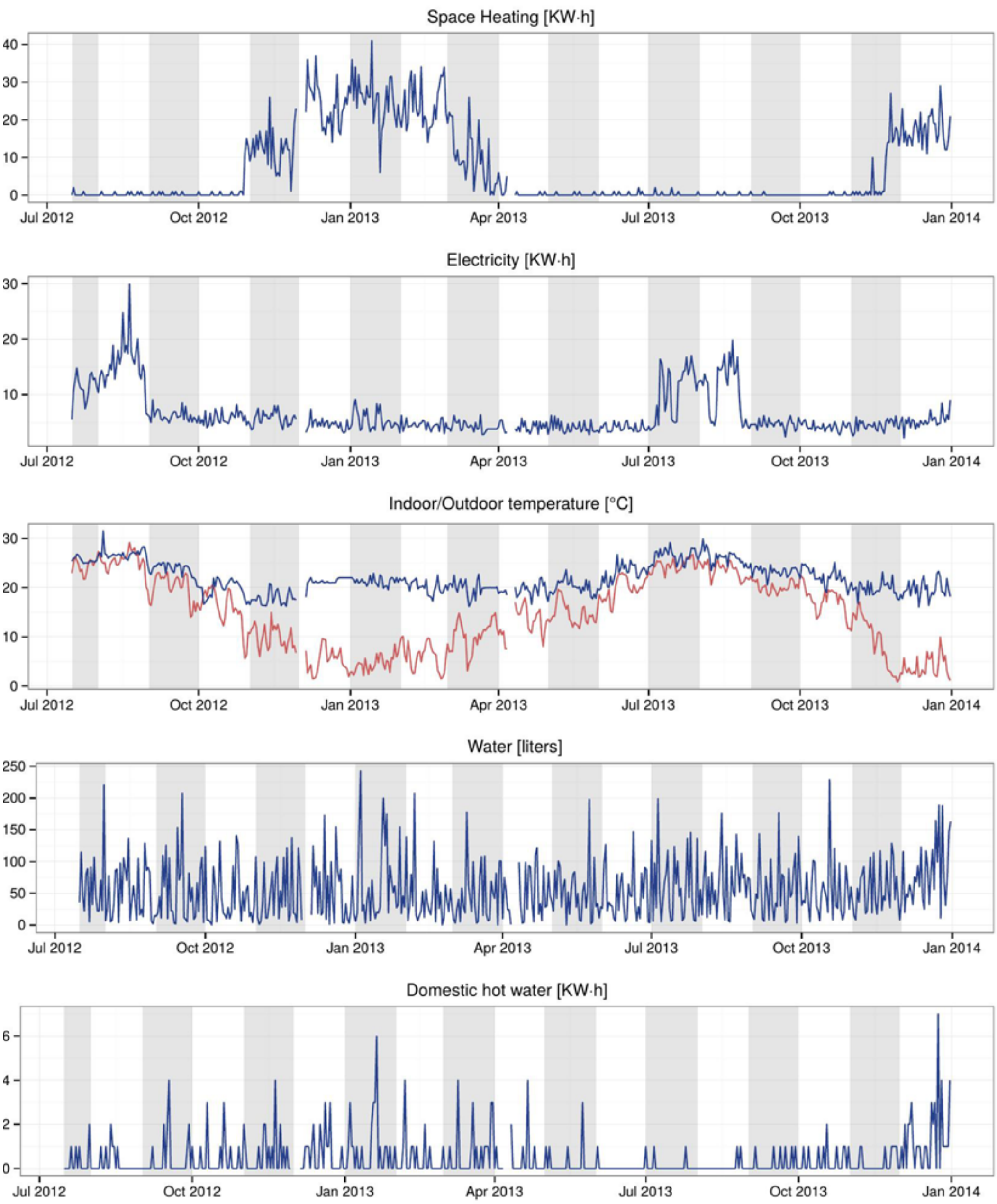


Figure 8. All available data from one apartment (daily aggregated)

Data examination; which part of the available time series can be used and for what purpose? As can be seen in figure 4 a heating period can be identified for which relevant information is available for building needs assessment, e.g. the thermal transfer through the building envelope. In figure 4 it can also be observed that the whole period, apart from two short cut periods, can be used for the analysis of the occupant behaviour derived from the electricity consumption. Before starting the actual analysis data processing is applied that includes non-parametric filtering like spike analysis (often linked to behavioural consumption) and other smoothing techniques and averaging. Statistical tools may investigate on correlation of input signals (like space heating or electricity consumption and outdoor temperature) and lead to adaption of the analysis process.

It has been observed from monthly accumulated data that energy consumption for these apartments vary enormously when expressed in kWh/m^2 and even kWh/person. In figures 6 and 7 the monthly figures are plotted for the cold period for all available apartments. Note that the exposed outer envelope surface has been used. Some of the apartments have not been occupied during a certain period which explains the zero energy requirements. Further study of the correlation between energy usage and space volume, is underway.

Hidden Markov Model Approach.

Given similar residential dwellings, huge variability in the energy consumption can be observed (see figures 6 and 7). This is mainly due to the different behaviours of the occupants. Considering there is a limited amount of direct observations of occupant presence and behaviour, the opportunity/potential for indirect classification of the occupants' behaviour is present.

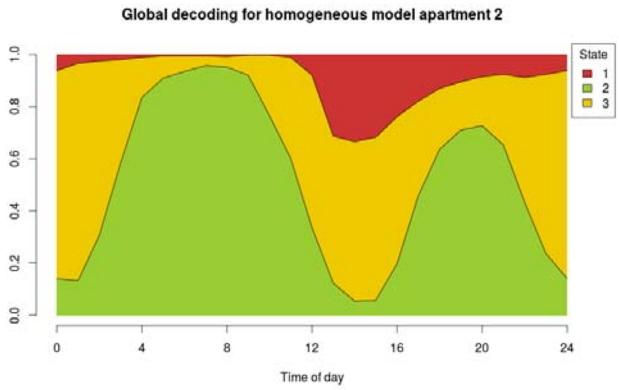


Figure 9. Average probability profile w.r.t. time of day.

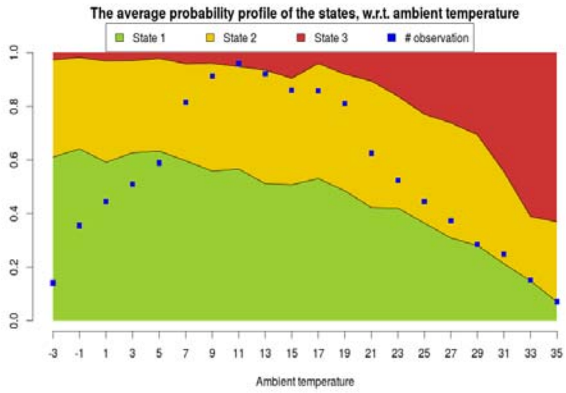


Figure 10. Average probability profile w.r.t. ambient temperature.

By applying a homogeneous hidden Markov model on the electricity consumption of an apartment, a number of states describing the data are obtained. In a hidden Markov model (Figure 11), the state is not directly observable, but output, dependent on the state, is observable. Each state has a probability distribution over the possible output tokens. The most likely sequence of states called global decoding [4] is determined. From the global decoding, dependencies of explanatory variables can be investigated (Figures 9 and 10).

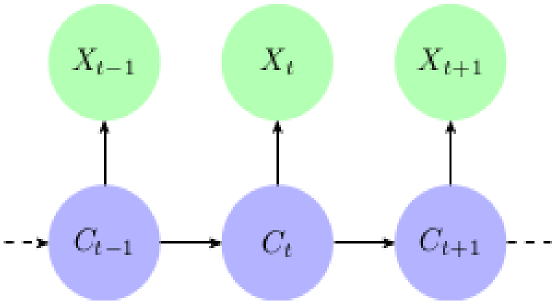


Figure 11. Directed graph of a 1 order hidden Markov model

This is used to classify/interpret the states and further develop the model by integrating the dependencies in the model structure. The application of these models are twofold 1) to separate the occupant energy consumption and the building energy consumption, and 2) forecasting of the future energy consumption.

Hidden Markov Models Applied

Homogeneous hidden Markov models were applied on 3 different apartments. The main differences between the apartments/occupants are summarized in Table 2. This prior knowledge, obtained through users surveys, can help in the interpretation of the states and validation of the model fits.

Table 2. Selection of data from occupant survey

Apartment:	**2**	**5**	**18**
Number of occupants	1	2	5
Air-condition	Yes	No	No
Hours empty on a weekday	3-5	>10	<2
Source of income	Pension	Work	Work

The states for the fitted models have been colour coded in accordance to their mean values, green is low-, yellow is medium- and red is high-consumption. This is the initial interpretation of the states for all the apartments. For apartment 2, dependence on both time of day and ambient temperature was found (Figures 9 and 10). For apartment, 5 and 18 only dependence on time of day was found (Figure 12). The dependence on ambient temperature for apartment 2 seem to be due to the air-

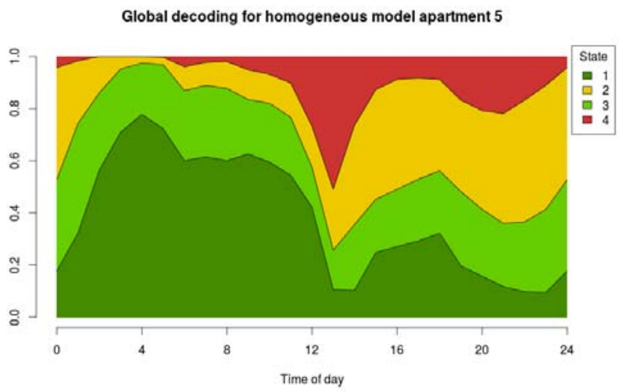


Figure 12. Average probability profile w.r.t. time of day.

conditioner, since apartments 5 and 18 do not have air-conditioner and no dependence on ambient temperature was found for these apartments. For apartment 18, a 3 state model was found suitable. Based on the average probability profiles dependent on time of day, (Figures 9 and 12) the “green” low consumption states have higher probabilities in the night and for apartment 2 and 5 also in the afternoon/evening. For apartment 18 the probability of the “green” state was low during the day. These occupancy profiles correspond well to the survey in Table 2 and to the boxplot electric consumption distribution by time of the day of figure 13. These can be interpreted as “asleep or away”. The “yellow” and “red” states can be interpreted as “home, medium consumption” and “home, high consumption” respectively. With the sequence of the global decoding it is possible to select data from other smart metering data, dependent on a certain state. For example space heating data could be investigated for conditions when the most probable state is “asleep or away”.

Since dependence on time of day was found for all 3 apartments time dependent inhomogeneous hidden Markov models were fitted for the 3 apartments. In the inhomogeneous HMM, each state has a probability distribution over the possible output tokens which is dependent on the time of day.

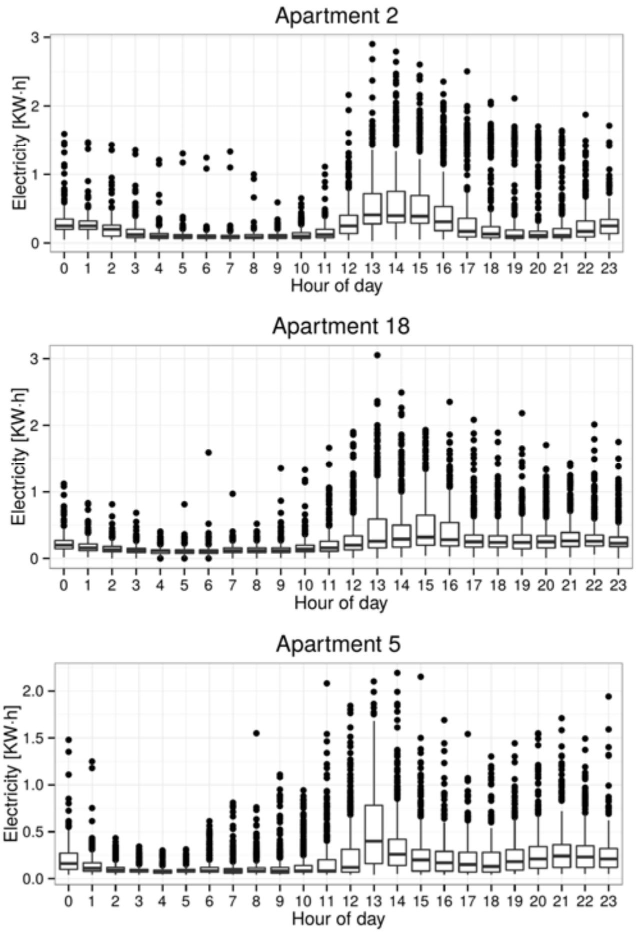
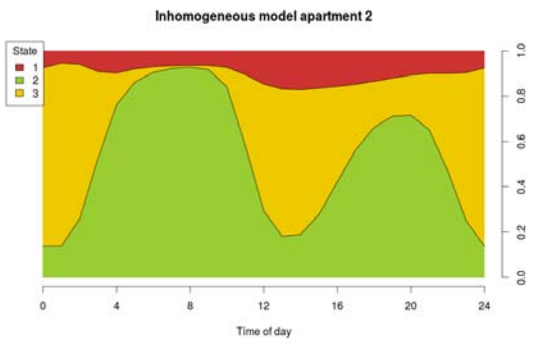


Figure 13. Boxplots of the electricity consumption by time of the day.

Comparing the daily profiles from the global decoding of the homogeneous models (Figures 9 and 12) with the daily profiles of the inhomogeneous models (Figures 13 and 14). They resemble each other for a given apartment, but the “red” state of apartment 2 is not captured. This might be due to the dependence of the ambient temperature which did not enter this model. Hence further model development is needed for apartment 2.



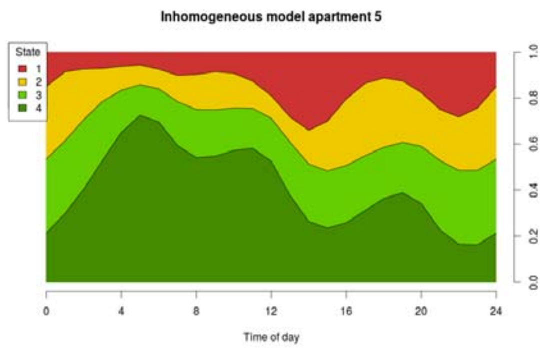


Fig 13. Probability of states given time of day Fig 14. Probability of states given time of day

It is noted that the homogeneous profiles are based on the global decoding which is data driven, where the inhomogeneous profiles only are based on the model parameters. These inhomogeneous models can be used for forecasting distributions for future energy consumption, while we use homogeneous HMMs for identification and classification.

Conclusion

Dynamic evaluation methods, in conjunction with statistical methods, are available to be integrated in smart grid environments to support the optimised use of energy. Metering data will make available huge amount of detailed information on energy use that may give information on the energy performance of buildings as well as the energy consumption by its occupancy for using appliances, their behaviour as well as specific non- building related issues. With the dynamic techniques it is possible to determine how well a building is insulated, combined with its wind sensitivity for the prevailing wind directions, its ability to passively use solar heating and the user behaviour occupancy profiles. These analysis techniques could be used for improved balancing of energy supply, demand and storage at distributed level and for individual dwellings.

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[3] Nielsen, H. A., Mortensen, S. B., Bacher, P., Madsen, H., 2010. Analysis of energy consumption in single family houses. In: DYNASTEE, 11-12 October 2010, Brussels.

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Measured Results of Phased Shallow and Deep Retrofits in Existing Homes

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Abstract

The U.S. Department of Energy (DOE) Building America program, in collaboration with Florida Power & Light (FPL), is pursuing a phased residential energy-efficiency retrofit program in Florida. This research is to establish annual energy and peak energy reductions from the technologies of two levels of retrofit – shallow and deep, with savings levels at the high end expected to reduce whole-house energy use by 40%. The Phased Deep Retrofit (PDR) project, has installed staged energy-efficiency retrofits in a sample of 60 existing, all electric homes.[1] Energy end-use savings and economic evaluation results from the phased measure packages and single measures are summarized along with lessons learned.

Background

Verified savings from residential energy retrofit programs are of considerable interest. An early large-scale evaluation and audit program in the 1980s achieved modest energy savings in the Hood River Conservation Project. There, Oregon homes received comprehensive retrofits of 15 improvements with a verified 12% savings and a 91% participation rate among several utilities' territories [1].

During the 1990s in Florida, the Florida Solar Energy Center (FSEC) demonstrated a 14% energy savings in ten retrofitted Habitat for Humanity homes [2]. In a more aggressive single project in an occupied home, FSEC demonstrated a marked reduction in measured energy use by 45% [3]. Another occupied home has been progressively retrofit in recent years to obtain zero net energy [4]. However, no project has attempted such improvements in a larger sample of contemporary U.S. homes. This project aimed to collect real-world energy use data on a highly instrumented home sample with easy-to-install, shallow retrofits performed in each to coincide with detailed audit data collection that would allow targeted deeper retrofits to be installed in a sub-sample.

Phased Deep Retrofit Project

Detailed audit data was obtained from all homes including house size and geometry, insulation levels, materials, finish, and equipment. A blower door test was completed on each home. Detailed photographs were also made of home exterior, appliances and equipment, and thermostat. Flow rate of shower heads was measured during the shallow retrofit, and pre- and post-retrofit duct testing was conducted on deep retrofit homes.

The homes are located in Central and South Florida, with varied construction characteristics. Figure 1 shows the geographic distribution of study sites over the state. The climate is cooling dominated with humid conditions. Built between 1942 and 2006, the homes averaged 165 m^2 in living area, with an average occupancy of 2.6 persons. As is typical in this region with nearly non-existent winters, the homes only have minimum insulation levels: ceilings typically have a U-value of 0.19 W/m^2-K and walls typically are insulated to 0.5 W/m^2-K or less. Analysis shows that much of the identified cooling loads in this region come from internal heat gains from appliance energy consumption that must be removed by the space cooling system. Envelope cooling loads are primarily confined to roof/ceiling and window shading.

Homes were audited and instrumented during the second half of 2012. Shallow retrofits came in spring 2013 with deep retrofits in summer and autumn.

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[1] Four homes dropped out of the project over the year; thus results from 56 homes are summarized here.

Figure 1. Geographic distribution of the PDR sites in the State of Florida.

End-use energy data were collected to evaluate energy reductions and the economics of each retrofit phase. Monitoring included whole house power and the various end uses, heat pump compressor, air handler and resistance heat, water heating, clothes dryer, range, refrigerator, freezers, swimming pool pumps and several spare circuits to pick up non-conventional end-uses [5]. This was supplemented by portable loggers to take indoor temperature and humidity data as well as a portable power logger to record energy use of the home entertainment center, game systems, and home office/computer workstations. Hourly data were retrieved daily over the internet via broadband connection. Ambient temperature and relative humidity were obtained from nearby weather stations.

Monitored Data

A dedicated website hosts the monitored energy data from the project: http://www.infomonitors.com/pdr/. A graphical summary of each site's eleven energy end-uses is shown by the stacked bar presentation in Figure 2 for all of 2013 which includes a portion of the post shallow retrofit period. A consistent color-coding by end-use is used in all the charts. Measured average annual consumption across sites was 42.8 kWh/day, although highly diverse end-uses suggest a complex challenge for efficiency programs. In the pie chart shown in Figure 3, no single end-use dominates. A second graphic, Figure 3, shows the average end-use make up for the entire sample for all sites estimated prior to the installation of the shallow retrofits. Heating, cooling and water heating only comprised 45% of measured consumption. Moreover, difficult-to-tackle loads such as clothes dryers and home entertainment centers, accounted for 10% of use and home office, game station, lighting, fans and other plug loads were fully 25% of consumption. Average pool pump energy reported in this synopsis is for all 56 sites in the overall sample. When confined to the eighteen pool sites, pump consumption averaged ~10 kWh/day.

Shallow Retrofits

Shallow retrofits were conducted in all 56 project homes from March to June 2013. The energy reduction measures were chosen based on ease of installation. These targeted lighting (CFLs and LED lamps), domestic hot water (wraps and showerheads), refrigeration (cleaning of condenser coils), pool pump (reduction of operating hours), and the home entertainment center ("smart plugs"). Measures were implemented to various degrees and not all measures were conducted in all homes.

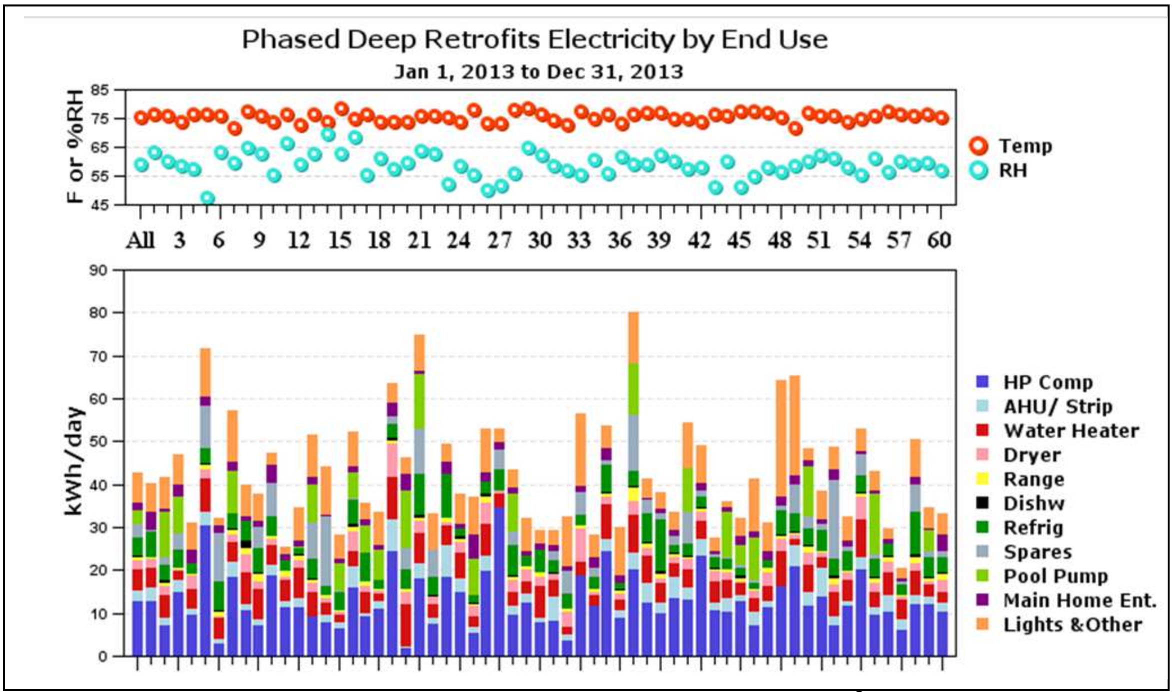

Figure 2. End use energy by site over 2013 in the total PDR sample.[2]

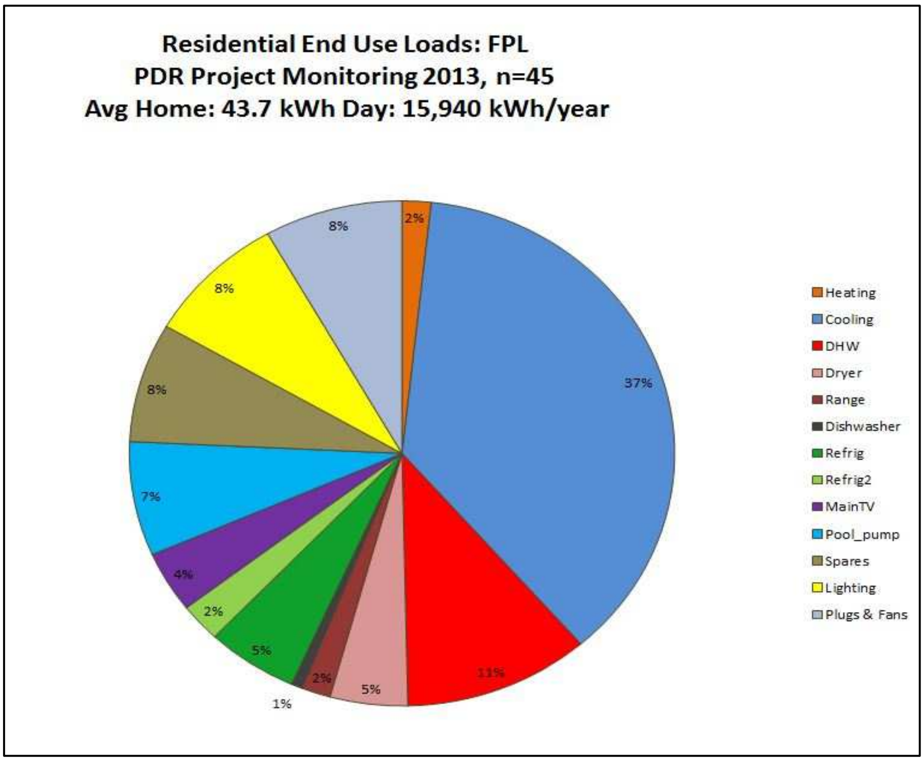

Figure 3. Average energy end-use in 2013 in the PDR sample.

Thirty-four percent of the homes in the dataset had swimming pools. Of these 19 pool homes, nine homeowners already had their pool pump timer set at or below the measure threshold of five hours/day. Ten homes had their pool pump timers reduced to ≤ six hours/day. On average, pump time was reduced by two hours/day.

2 HP Comp is the heat pump or air conditioning compressor. AHU/Strip is air handler unit, strip electric resistance heating. Spares circuits 1-4 include potpourri of loads: additional televisions, computer work stations, gaming consoles, hot tubs, fountain pumps and room air conditioners.

Most houses already had some energy efficient lighting (defined to be CFL or LED types). Indeed, one home already had 100% LED lighting, whereas six others had mostly CFLs and needed fewer than 20% of bulbs changed. Owners sometimes objected to lighting retrofits for some lamps which were not changed. A total of 55 homes were affected by the lighting retrofit. On average, 54% of bulbs were replaced with CFLs or LEDs.

An effort was made to reduce domestic hot water energy through two means: (a) reducing use through low-flow showerheads and (b) reducing storage thermal losses by insulating tanks and hot or warm pipes. Space limitations generally restricted the application of RSI-1.8 thermal blankets, so most homes received a smaller RSI-0.6 wrap. Exceptions to tank wrapping include one tank already insulated, one heat pump water heater, and three homes where the tank was partially inaccessible. All accessible hot or warm water pipes were insulated. A total of 53 homes had domestic hot water reduction measures installed: 26 homes had at least one showerhead replaced with a low-flow head and 51 homes had a hot water tank insulated with RSI-0.6 insulation around all accessible hot and warm pipes. Fifty homes had fouled refrigerator coils cleaned. Figure 4 shows observed daily power for affected end-uses at site #54 during this sixty-one day analysis period. The vertical, dashed, purple line indicates the shallow retrofit date.

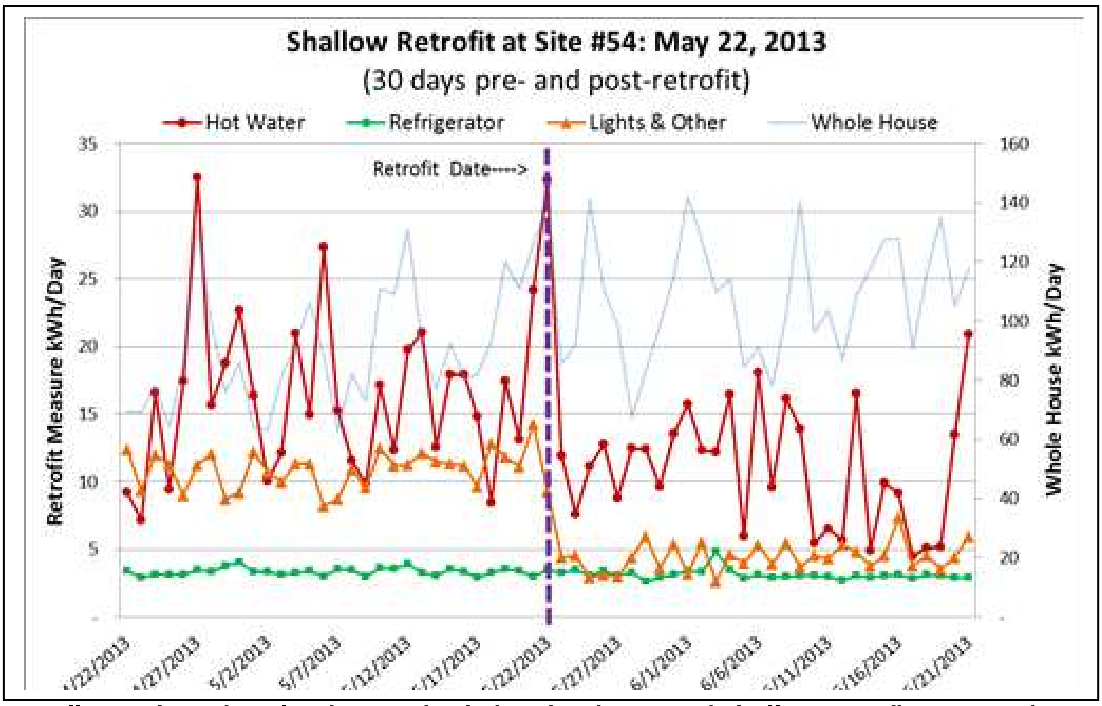

Figure 4. Illustration of evaluation method showing impact of shallow retrofit at PDR site #54 spanning one-month period before and after installed retrofit measures.

The plot shows how lighting and domestic hot water heating retrofit measures produced immediate reductions to energy use (approximately 50% and 31% savings, respectively). Though not visually obvious, refrigerator coil cleaning also generated modest savings (6%).

The shallow retrofit savings were evaluated in two ways; a weather-adjusted 30-day, pre- and post-retrofit end-use comparison for all 56 sites and a 30-day, same calendar month of different years with similar weather conditions, pre- and post-retrofit end-use comparison for 17 sites. Estimated whole house savings were similar between the two approaches, at 9% and 8% savings, respectively. Table 1 summarizes whole house and end-use savings results which were very close to the 10% savings estimated before the retrofits were done. One surprise from the project was that after the lighting retrofits were undertaken; we found that measured interior cooling thermostat temperatures were adjusted downwards by 0.4^{o}C, likely in response to the change in internal heat gains and also the interior space mean radiant temperature. Thus, space cooling consumption was also lowered from changing the interior lighting systems.

Table 1. Shallow Retrofit Savings: Two Evaluation Method Results

Shallow Retrofit Average Daily Savings	Hot Water (kWh)	Refrigerator (kWh)	Pool Pump (kWh)	Lights & Other (kWh)	Whole House (kWh)	% Whole House Savings
30 Days Pre-Retrofit	5.6	2.4	10.7	7.7	40.5	
Weather-Adjusted, 30 Days Post Retrofit	5.2	2.3	8.0	6.4	36.3	
Weather-Adjusted, 30 Day Pre- vs Post-Retrofit	0.4	0.1	2.7	1.2	4.2	9.2%
October 2012	4.2	3.2	7.4	8.5	45.3	
October 2013	3.6	2.3	7.2	6.1	41.7	
October 2012 vs October 2013	0.6	0.9	0.2	2.5	3.5	7.9%

Overall, the measures generating greatest initial savings were pool pumps followed by the lighting retrofit and then water heating. The cost-effectiveness of the shallow retrofits was promising. Averaged per site energy savings from the shallow retrofits was 1,310 – 1,530 kWh/year. The average total cost of the shallow retrofits was estimated to be $372 of which $250 was hard costs and the remainder was labor. A simple payback is reached for each end-use in five years or less and in two years with all measures taken together.

Deeper Retrofits

Deeper retrofits were conducted on 10 of the Central Florida project homes beginning in August 2013 and were completed in early 2014. Measures associated with this second phase of the project included major modifications to the heating and cooling system (HVAC), including replacement of air source heat pumps, duct repair and addition of learning thermostats. To reduce water heating energy, heat pump water heaters were installed. Appliances were replaced when old and inefficient; pool pumps were replaced with variable speed units, and ceiling insulation was augmented where deficient. Added floor and ceiling insulation was installed as audited. A series of more extensive retrofits will take place the spring of 2015 (window and wall insulation retrofits in a subset of homes).

Summary of Cooling Energy Savings in Deeper Retrofits

Table 2 shows the measured heat pump retrofit savings by site. In all but one case, the existing air conditioner or heat pump was replaced with a 10.6 kW two-speed COP 5.0 Carrier 25HCB6 heat pump (this unit was chosen to be compatible with the learning thermostat). Ducts were also tested and sealed at each site and a NEST learning thermostat was installed except at Site #10. At Site #10 a multi-speed COP 5.3 Carrier Infinity Model - 25HNB936A310 heat pump with a variable speed van coil (FE4ANF003) was installed.

Figure 5 graphically displays an example of HVAC retrofit savings analysis at Site #19. Post-retrofit savings at this site averaged 47% (30 kWh/day). There is a large apparent reduction in cooling energy use from week before to week after (76.8 kWh to 37.9 kWh/day). However, the post period weather was cooler. Figure 6 shows that some of the changes seen in the weeks after the retrofit on August 26, 2013 are associated with a lower average outdoor temperature. Also, the occupants with the NEST learning thermostat maintained a very slightly higher temperature than before the retrofit.

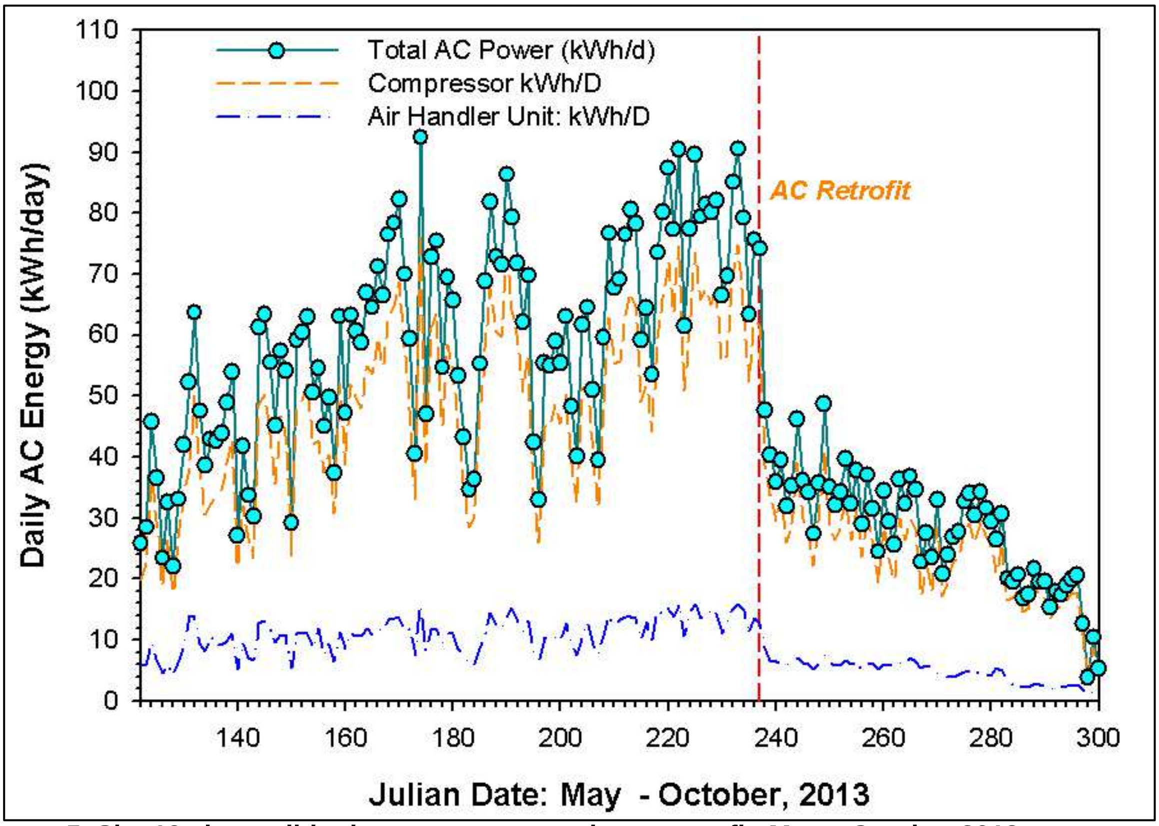

Figure 5. Site 19 air conditioning energy: pre and post retrofit, May – October 2013.

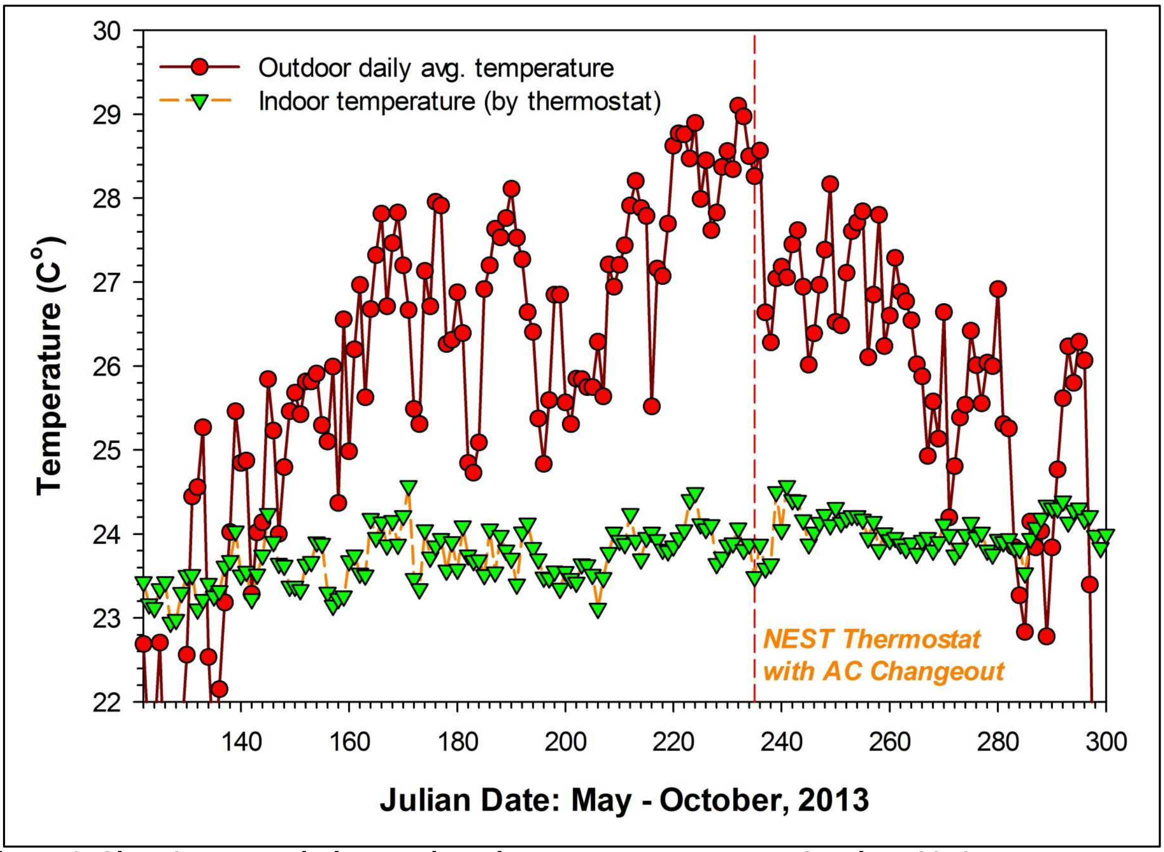

Figure 6. Site 19 average indoor and outdoor temperature May – October, 2013.

Table 2. PDR Cooling Energy Savings Analysis (May – October, 2013)

Site	Pre kWh	Post kWh	Savings kWh	Percent Savings (%)	HVAC Saved (%)	Thermostat (°C)		Temperature-Related	
						Pre-Retrofit	Post-Retrofit	Savings (%)	Learning Thermostat Savings
7	38.3	33.8	4.5	12%	18%	22.3	21.7	-6%	-6%
8	35.4	14.7	20.7	58%	54%	25.5	25.8	4%	4%
10	57.7	25.9	31.8	55%	63%	25.4	23.2	-13%	*
19	61.0	30.8	30.2	50%	47%	23.9	24.1	3%	3%
26	41.2	21.8	19.4	47%	48%	23.9	23.1	-1%	-1%
30	19.3	16.5	2.8	15%	23%	25.4	24.9	-8%	-8%
37	40.0	33.6	6.4	16%	28%	25.7	24.3	-12%	**
39	23.2	15.0	8.2	35%	31%	25.7	26.2	4%	4%
40	32.4	20.6	11.8	36%	35%	24.1	24.3	1%	1%
51	39.7	21.5	18.2	46%	48%	26.9	26.2	-2%	-2%
Avg.	38.8	23.4	15.4	37.0	39.5	24.9	24.4	-1.9%	-0.6%

★ No learning thermostat installed
★★ Received improper instruction relative to learning thermostat operation

To evaluate weather influences, we used the pre and post daily air conditioning data and then regressed daily cooling kWh against the average daily air temperature (Figure 7).

Measured average savings for a typical summer day in Central Florida with an average temperature of 26.7°C were 15.4 kWh/Day or 37% of pre-retrofit consumption from the combination AC replacement/duct repair and learning thermostat installation. Using regression techniques with the outdoor weather and temperature maintained indoors we were able to separate out the influences of the AC retrofit and duct repair from the learning thermostat installation. We saw that the AC and duct repair saved an average of 40% of pre-retrofit consumption, but that lower temperatures were generally chosen, even with a learning thermostat so that the average final savings were about 37%.

In the single site without a learning thermostat, the interior temperature maintained post retrofit was 2.2°C cooler. In homes with the learning thermostat, it was still about 2.2°C cooler post retrofit. In four of the nine NEST sites there were post-retrofit savings from the learning thermostat of 1 – 4%. However, these were marred by others with negative savings. We do not know why sites chose lower temperatures post retrofit, although it is possible that the households chose a lower temperature to compensate for the learning thermostat attempts to raise the interior temperature. It is known from occupant feedback, that Site #7 defeated the "auto-away" feature to prevent the thermostat from increasing the interior temperature while they were not home.

A key caveat is that we cannot evaluate what learning thermostats will do to systems where the AC system is not being changed. AC retrofit may very well alter occupant expectations. Thus, the large degree of temperature take-back seen at Site #10 may be typical. A previous study replacing five air conditioners with high efficiency units in 2001 showed an average temperature related take-back of 0.6°C [6]. The isolated effect from the learning thermostats cannot known without further research – which we anticipate being able to attempt by a series of NEST-only retrofits to some of the shallow retrofit group in the summer of 2015.

Heat Pump Water Heaters

Eight existing electric resistance water heaters in the deep segment were replaced with new heat pump water heaters in eight Central Florida homes in September and October of 2013. Measured average savings was calculated at 64% (3.62 kWh) by comparing thirty days of pre and post-retrofit energy. Savings were slightly higher (66% or 3.77 kWh) after adjusting for the influence of weather as inlet water temperatures declined over the autumn period. These results are consistent with past research at different locations around the U.S. For instance, savings of 40 systems monitored in the Pacific Northwest showed an average savings of 51% [7]. Table 3 lists measured savings results from eight sites in order of installation date. A group of 47 homes where resistance water heaters were unchanged served as a control for normalizing to seasonal changes in water heating energy. Average energy use in the control group increased 4.4% when comparing the same thirty day period before and after the retrofit.

Table 3. Heat Pump Water Heater Retrofit Savings at 8 Sites (30 days pre and post)

Site	Install Date	kWh day Savings	Raw Savings	Control Group kWh/day Change	Control Group Change N = 47	Normalized Savings	Pre-retrofit Equip Capacity	HPWH Equip Capacity
Site 51	9/4/13	1.39	68.1%	0.03	0.9%	68.4%	151 L	227 L
Site 10	9/5/13	2.67	60.2%	0.07	1.9%	61.0%	189 L	227 L
Site 30	9/9/13	4.41	68.7%	0.13	3.6%	69.8%	151 L	303 L
Site 26	9/12/13	5.53	70.7%	0.16	4.7%	72.1%	208 L	303 L
Site 40	9/13/13	1.94	59.8%	0.19	5.3%	61.9%	151 L	227 L
Site 19	9/19/13	5.76	64.8%	0.22	6.5%	67.1%	189 L	303 L
Site 07	9/24/13	2.30	52.0%	0.17	4.9%	54.4%	151 L	227 L
Site 08	10/16/13	4.96	66.8%	0.26	7.0%	69.1%	189 L	303 L
227 L	average	2.08	61.4	0.12	3.3%	61.4%		
303 L	average	5.16	69.5	0.19	5.4%	69.5%		
Overall	average	3.62	63.9%	0.15	4.4%	65.5%		

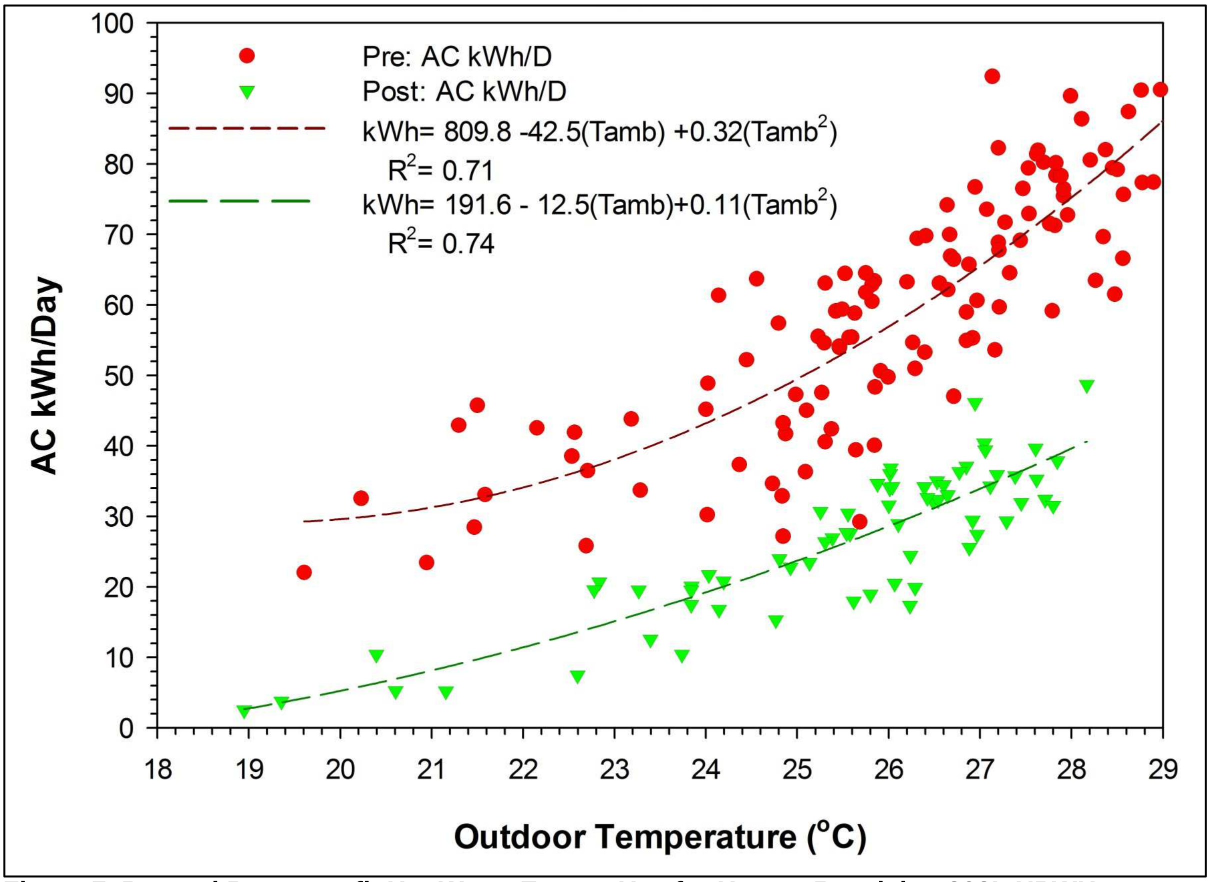

Figure 7. Pre and Post-retrofit Hot Water Energy Use for Homes Receiving 303L HPWHs.

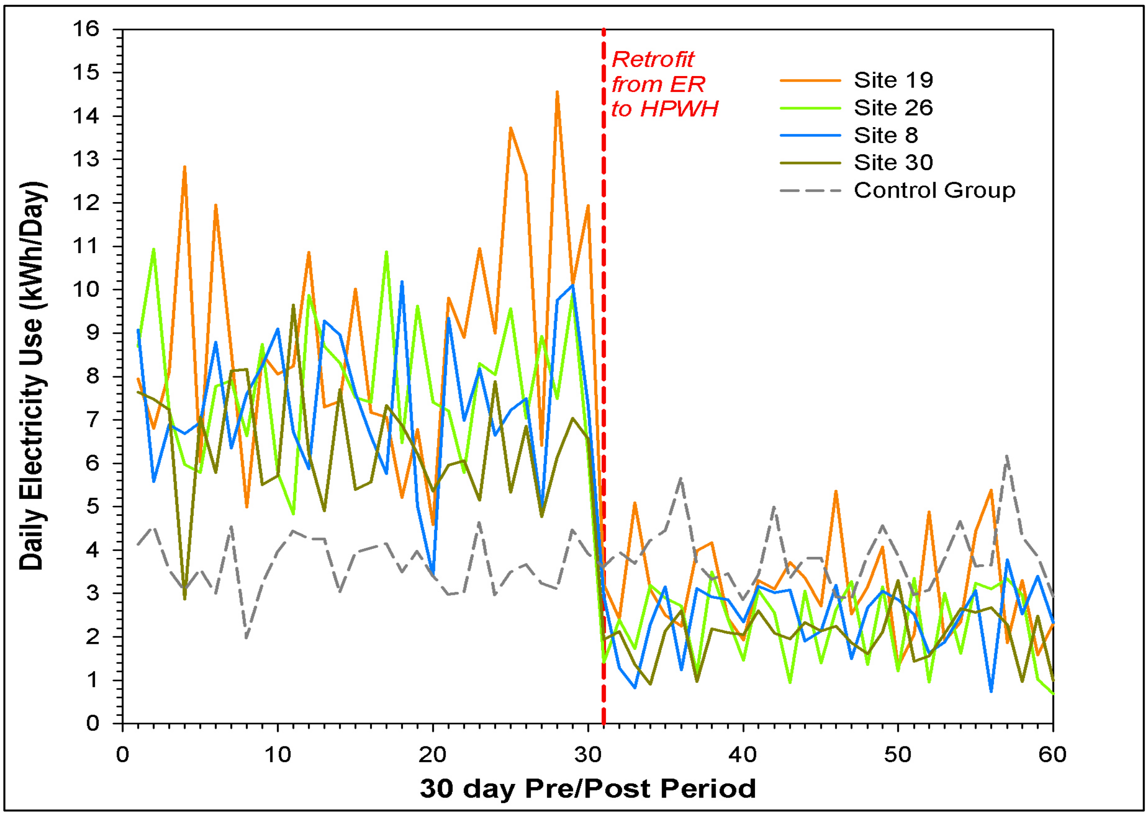

Figure 8. Pre and Post-retrofit Hot Water Energy Use for Homes Receiving 227 L HPWHs.

Appliance and Equipment Replacement

The deep segment of the project made high energy use refrigerators eligible for replacement as well as dishwashers and washers and dryers. Refrigerator replacement in three deep homes had average savings of 42% (1.3 kWh/day). Post-retrofit energy savings for the single dishwasher change-out to an Energy Star unit was 32% (0.5 kWh/day).

A more efficient washer and Energy Star clothes dryer was demonstrated in the project. This is important since electric resistance clothes drying accounted for 5% or 790 kWh/yr of annual energy consumption in the PDR sample. The *Samsung DV457A1* clothes dryer modulates fan speed and drying time to provide savings estimated in the laboratory to be approximately 25-30% (Ecova, 2013). In our field tests, the higher efficiency clothes dryer showed savings of 18% (0.6 kWh/day) for the eight homes where installed when evaluated over a 90-day period pre and post. Savings were highly variable; the home with largest use showed a 26% reduction, while some sites had negative savings associated with not choosing the most efficient cycle.

Measured pool pump energy was high in homes with pools, averaging about 3,400 kWh/yr in the 18 project homes prior to intervention. Savings from variable speed pumps installed at three pool sites within the deep retrofits were very large with reductions: 80 – 90% (8.8 to 16.8 kWh/day). However, we found only about half the potential savings were achieved unless the variable speed units were properly programmed. Figure 9 shows representative savings for Site 7. On September 24, 2013, the variable speed pump and new filter were installed resulting in a 90% reduction in measured energy use through December 15, 2013 (82 days). The 3 horsepower variable speed pump runs for 12 hours/day at 0.16 kW with average energy use of 1.9 kWh per day. With some two-million residential pools in the state of Florida, the potential savings of this measure are enormous. The average pool uses approximately 4,000 kWh/year for circulation, with demand that is often coincident with the summer peak (Parker, 2002).

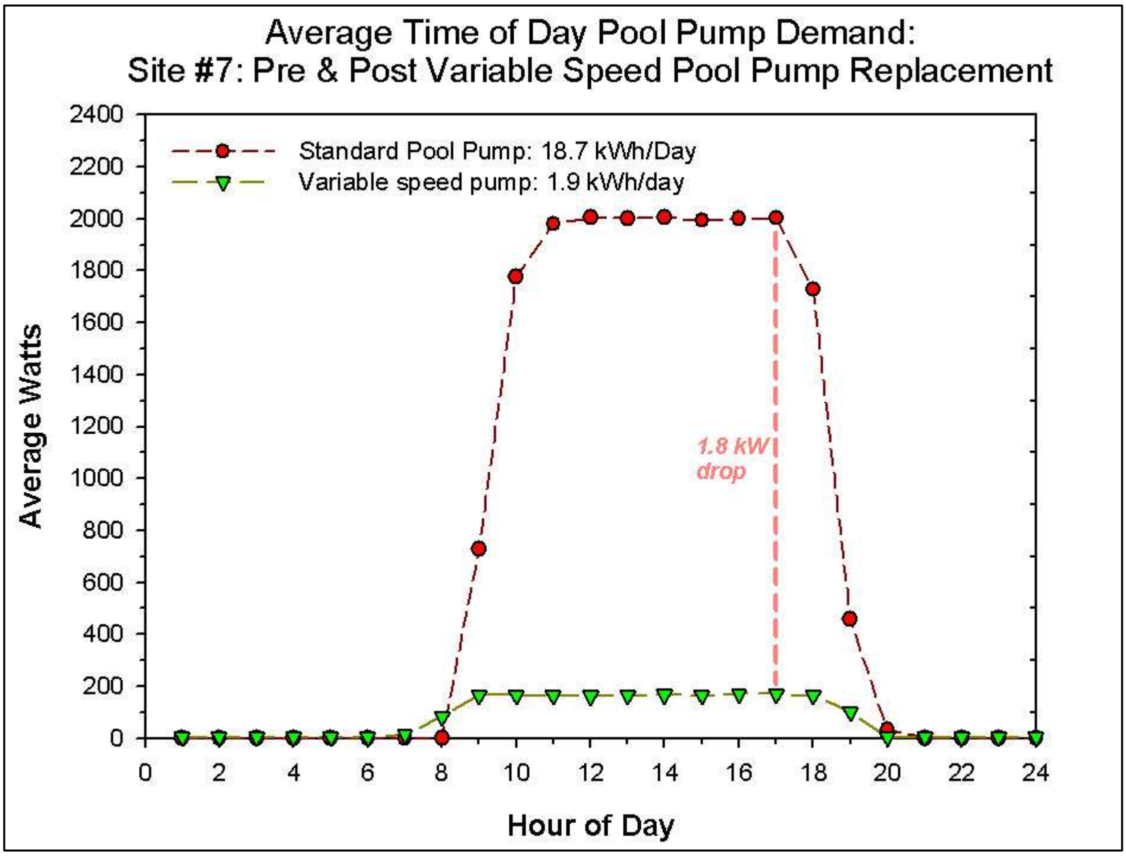

Figure 9. Time of Day Pool Pump Demand at Site #7; Pre (red) and Post (green).

Overall Savings for Deeper Retrofits

For the deeper retrofits, we conducted a preliminary assessment using the first few months of data on the six sites with consistent pre and post monitoring. Figure 10 shows the average load profiles for all end-uses on a deep retrofit sample before and after the retrofits. Comparing the four-month pre-retrofit period of October 2012 - January 2013 to the same post-retrofit period a year later, total savings for the post-retrofit period averaged 16.5 kWh/day, or 34%.

Final savings estimates were higher as this period included the energy-intensive summer period. Annualized savings averaged 38% (range 26-54%) or 19.4 kWh/day or about 7,000kWh/year. The installed costs of the retrofits, including both the shallow and deep segments and associated labor averaged $14,200. An important observation from the project is that if the appliances and heating and cooling equipment had been replaced at the time of burnout (end of the useful life of the appliances), the cost would only be about 50% of the cost of outright replacement. This indicates that refurbishment programs that replace equipment and appliances at end of their useful life will have better economics, although foregoing energy savings associated with immediate replacement. Even with the low electricity prices in Florida (~$0.12/kWh), the deeper retrofits appeared cost effective.

Finally, as we are collecting detailed hourly data on all the buildings it was possible to evaluate how the deeper retrofits influenced peak demand during the utility peak summer demand days. Figure 11 shows the peak demand of the all of the deeper retrofit group on the utility peak demand day of August 13, 2013 after the installation of the shallow retrofits, but before the deep retrofits. The same plot also shows the peak summer day of July 29, 2014 after the installation of the deeper retrofit for the same group of ten buildings. Even though the weather conditions were actually warmer in the 2014 day, the deeper retrofits evidence a 42% reduction in peak demand of the group of buildings during the utility peak period.

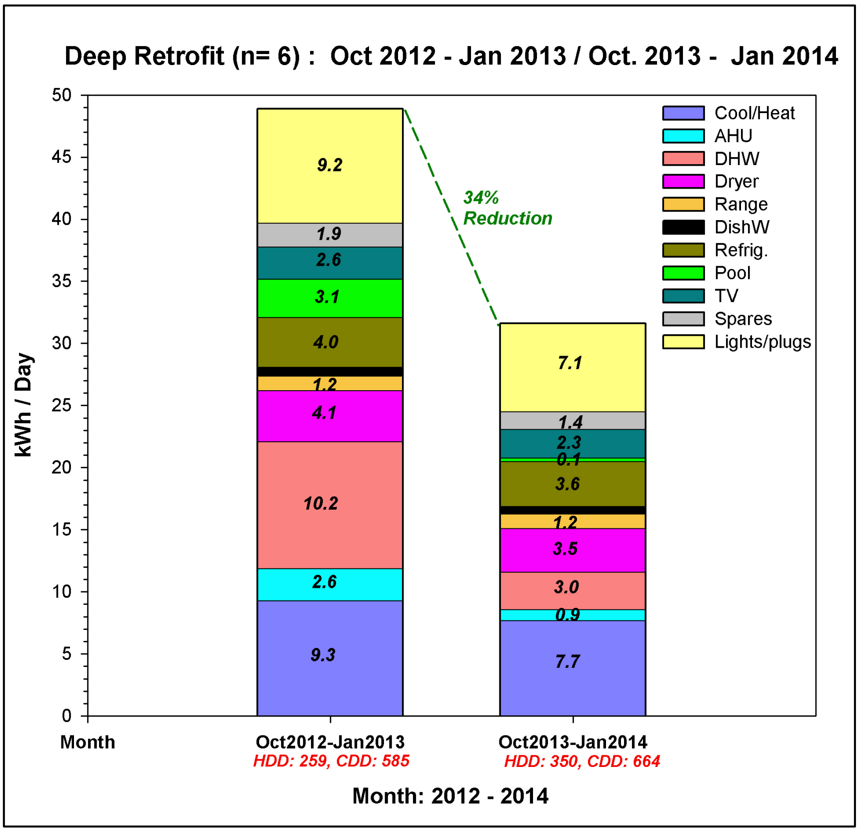

Figure 10. Avg end-uses in deep retrofit sample, October 2012 – Jan. 2013 versus Oct. 2013-January 2014.

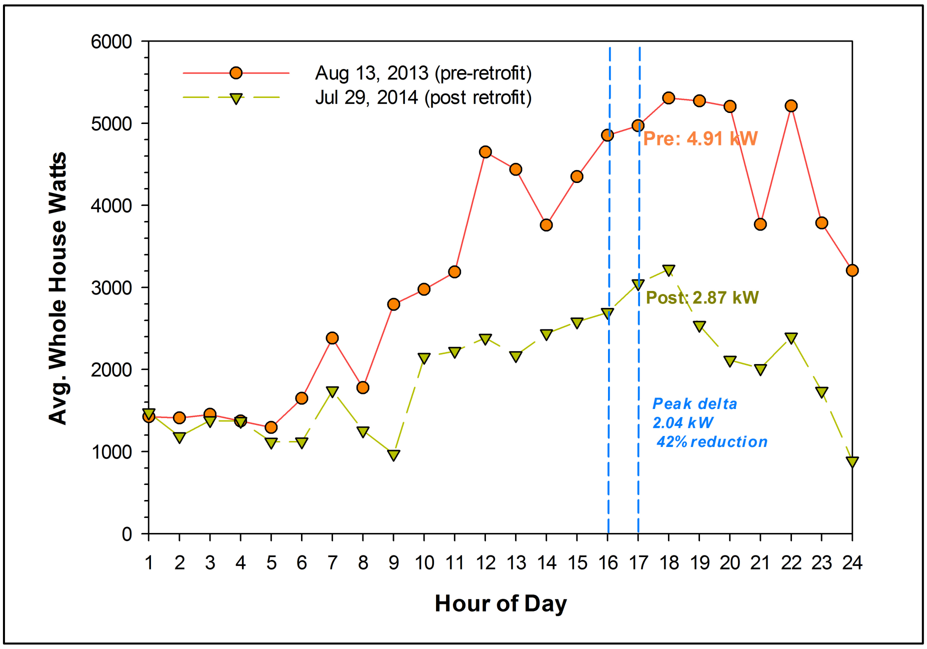

Figure 11: Peak summer day demand profile for the sub-set of ten buildings before and after deeper retrofits. Before (Aug. 13, 2013); After (July 29, 2014).

Conclusions

A Phase Retrofit Project in 56 homes in Florida found an average savings of 9% or about 4 kWh/day for shallow retrofits with very favorable economics. Moreover, the lighting retrofit showed evidence of having reduced space cooling needs after the shallow retrofits. Monitored cooling thermostat set points were increased by 0.4^{o}C after lighting change out without further intervention, indicating possible changes in the interior thermal environment

Results for the deeper retrofits in ten additional homes found savings of 19 kWh/day or 38%. Savings of HVAC replacement, heat pump water heaters and variable speed pool pumps all showed large and reliable energy reductions. Envelope improvements assisted with savings potential, although less so in Florida where space heating loads are very low. Utility summer peak day demand reductions were 42% for the deeper retrofit group. Average deeper retrofit cost was $14.2K although such costs could be cut in half if appliances and equipment was replaced at the end of its useful life.

Additional technologies such as heat pump clothes dryers are being evaluated in number of the heavily instrumented sites in the current year. Other conventional measures are being evaluated as well: highly insulated solar control windows and retrofitted wall insulation.

Acknowledgements

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Builder-Installed Electrical Loads in New Homes

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Abstract

The "builder-installed" electrical products are the appliances and components installed by the builder during construction and prior to occupancy. Some of these components are required by safety codes, such as smoke detectors, others are needed to support the communications infrastructure, and still others provide features that future occupants will find useful, such as remotely controlled garage door openers. We compiled a list of over 50 builder-installed devices that are likely to have continuous power consumption, and measurements of power consumption for a smaller group. Individual components consume very little power but a typical North American home can easily have 80 W of continuous power – corresponding to over 650 kWh/year – devoted to these components. The types of products and power consumption may be different in Europe or Japan. Techniques to reduce this energy use include: selection of lowest-power solutions when a range of power consumptions are available, more efficient circuitry and power management, a separate DC circuit to serve DC-powered appliances, and use of energy-scavenging sensors and controls in place of grid-powered components. A protocol to define and measure builder-installed loads, along with a recommended ceiling, might also stimulate savings.

Introduction and Background

An increasing fraction of residential electricity consumption falls into the "miscellaneous" category. This is the electricity consumed by devices that do not fit into core end uses such as refrigeration, water heating, cooling, etc., although there is no precise definition. Several terms are used to described these loads, including "plug loads", "other", and "MELs" (for "Miscellaneous and Electronic Loads"). Studies in several countries have identified MELs as an important problem because it continues to grow in both absolute and relative terms. For example, MELs is estimated to account for 26% of electricity use in US homes [1] but less in other countries [2]. These values cannot be directly compared because of different definitions and dates of the analyses but they all suggest that these miscellaneous loads are a significant fraction of current electricity use.

Reducing MELs is technically difficult to accomplish because the consumption is dispersed across a large number of appliances and electrical components, each of which draws relatively small amounts of electricity. At the same time, traditional policy tools, such as Minimum Energy Performance

Standards (MEPS), energy labels, and incentives have less impact, principally because of the high transactions costs required to achieve small energy savings per device.

We examine in this paper a subset of MELs, the “builder-installed” electrical products. These are the appliances and components installed by the builder during construction and prior to occupancy. The builder-installed subset is extraordinarily diverse but may nevertheless be susceptible to unique policy tools. We compiled a list of common builder-installed devices, report on their power consumption, and describe approaches to reducing their energy use. Our study focuses on homes and data from North America and Australia; however, many of the devices are similar to those found in Europe, Japan, and elsewhere. We focused on the continuous, or standby loads, from these devices rather than the “active” consumption. The active energy consumptions may be regulated by MEPS. Active-mode consumption may also depend on behavior and other factors that we are unable to evaluate and, in any event, are outside the builder’s control. In many cases, the fixed loads represent the largest fraction of these devices’ energy consumption.

Definition of Builder-Installed Products and Loads

“Builder-installed products” are the appliances and components put into a home during the construction process and before people occupy it. Builders typically install appliances and components because they are required by building codes or make the home more attractive to potential buyers or occupants. Some of the products are “hard-wired”, that is, need an electrician to install and cannot be unplugged. The principal categories of builder-installed products with continuous loads are listed in Table 1.

“Builder-installed loads” are the electrical consumptions of these products. These loads are described in terms of their Power (W) because many products draw power continuously, although they may have additional power levels while active.

The distinction between builder-installed and occupant-installed products is sometimes arbitrary. Some products and appliances may be selected and installed by either the builders or the occupants depending on local conditions. The distinction is also rapidly evolving. For example, builders install an increasing number of devices associated with information technology infrastructures that were formerly installed by occupants.

Table 1. Categories of energy-using builder-installed products

Category	**Examples**
Required by building code for safety	Ground fault circuit interrupters (GFCIs)

Provides security	Security system, intercom
Associated with heating, cooling, ventilation, hot water	Heating controls
Communications and IT infrastructure	Cable modem, Wi-Fi router
Amenities & Features	Remote control features on blinds, gas fireplace

These categories are only roughly defined because many products provide multiple services. The selection and number of these devices vary widely with the location and home. Expensive homes typically have more of everything.

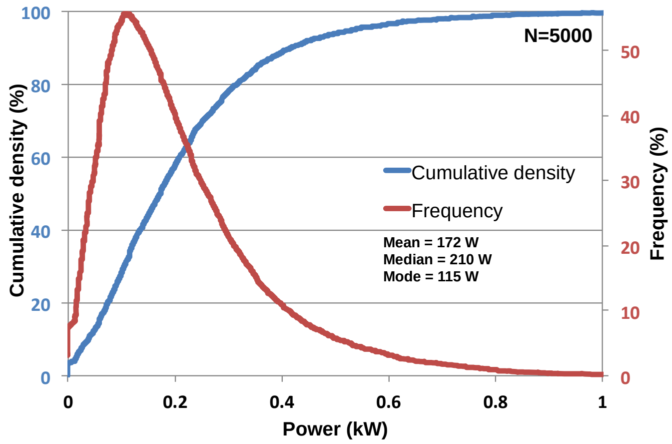
Earlier Investigations of Builder-Installed Loads

Some builder-installed products have been measured in laboratories and in stores. For example, The Australian Greenhouse Office (Energy Efficiency Strategies 2004) measured power consumptions of smoke alarms. Deforge [3] examined standby power of ground fault protection circuits. The standby power consumptions of various builder-installed appliances –dishwashers, tankless water heaters, etc.– are also sometimes reported by manufacturers in their product manuals.

The aggregate electricity consumption of a home at the completion of construction, but prior to occupancy, has not been widely investigated. In 2006, Brown et al. [4] surveyed 13 new, but unoccupied, homes in the United States and estimated the loads from builder-installed devices. Through field studies, sub-metering, and measurements of individual devices, they estimated that builder-installed loads were responsible for a continuous power draw of about 50 W (or 440 kWh/year).

Borgeson [5] used data from smart meters to identify the lowest hourly consumption over one year in 25000 existing California homes. Figure 1 shows a cumulative distribution of power use among the homes.

Figure 1. Distribution of minimum power loads – lowest hour during the year—for 5000 California homes.



About half of the homes had a minimum load greater than 0.25 kW, corresponding to roughly 2200 kWh/year. Another California study [6] of 2750 homes found an average minimum load of 218 W. The minimum observed load in these existing homes does not correspond directly to builder-installed loads but it establishes an upper limit. Most of the core end uses (such as refrigerators, water heaters, and lights) are switched off or not cycling during the hour of minimum load, so builder-installed loads are responsible for a significant fraction of these observed minimum loads. The widespread installation of smart meters--especially in new homes--will make it easier to measure power consumption of newly constructed but unoccupied homes. The presence of smart meters also makes it possible to quickly measure the minimum power of vacant, existing homes.

Typical Builder Installed Products With Continuous Electrical Loads

Tables 2a-e (end of paper) list many builder-installed products with continuous electrical loads. The products are divided into the categories proposed in Table 1. No home will have all of these devices and some homes will have more than one of certain devices. Some characteristics of these products are described below. The intent is not to be comprehensive; rather, it is to illustrate the diversity of products. Homes in Europe or Japan may have other builder-installed components drawing power continuously.

Required By Building Codes

An increasing number of electrical devices are required by building codes to ensure the safety of the occupants and the structure. New homes in North America homes are required to be equipped with technologies to prevent accidental electrical shocks, such as ground fault circuit interrupters (GFCIs). Outlets with this safety feature must be installed in kitchens, bathrooms, laundry rooms, and in any location where standing water may occur. Arc-fault circuit interrupters (AFCIs) and other kinds of circuitry are installed at the panel to prevent fires by detecting hazardous short circuits and disconnecting mains power. These circuits also draw power continuously.

Smoke detectors and alarms have been required in U.S. homes for decades. Most residential smoke detectors were battery-powered, which require periodic replacement. Studies found that many batteries were not replaced and numerous serious fires could have been prevented with functional smoke detectors [7]. As a consequence of these findings, building codes are being revised to require hard-wired smoke detectors to eliminate the problem caused by dead or removed batteries. Fire codes typically require a smoke detector in each bedroom, on each floor, and several other key locations. Carbon monoxide alarms are required in houses with combustion appliances. As a result, a new home could easily contain over eight smoke and carbon monoxide detectors.. Builders may install other kinds of safety-related sensors and alarms in special situations. For example, homes vulnerable to flooding might have special water alarms. All types of sensors are becoming networked so, again, the Wi-Fi router, is arguably a necessary component of safety and security systems.

Security-Related Loads

Builders install some products to provide security to the occupants. Door bells and their associated transformers, were among the first continuous loads in homes. Modern homes and apartments, especially those in Japan and Korea, have sophisticated communications systems between persons at the entryway and the occupants. Their features include a "doorbell", audio and video connections, and entry control. Almost all new U.S. homes with garages are equipped with garage door openers, usually with a remote controls. These door openers have child safety features that remain active even when the garage door is closed. Homes throughout the world are equipped with security systems to detect intrusion. These systems are installed both as retrofits and by builders. With the dramatic reduction in cost of video surveillance, new homes are being equipped with a network of video cameras. Some systems are connected to the Internet, thus requiring the builder to install a Wi-Fi router and Internet connection.

Loads Associated With HVAC Equipment

Builders are typically responsible for installation of Heating, Ventilation and Air Conditioning (HVAC) equipment – indeed, this may also be required by code. Nearly every type of HVAC system now includes some sort of continuous load. A recent DOE regulation established the maximum allowable "off-mode" consumptions at 30 W for most central air conditioners and heat pumps [8]. Thermostats typically operate off low-voltage power supplied through a transformer. Many building codes now require continuous mechanical ventilation, which is provided by small fans. Heat pumps have crankcase heaters that, depending on the control strategy, continuously draw power. Heating systems based on circulating hot water require a pump that is selected and installed by the builder. If incorrectly commissioned, these pumps can operate all the time. Equipment designed to provide local cooling or heating, such as room air conditioners and ceiling fans, are nearly always installed with remote controls that have small, continuous loads.

Tankless (or demand) water heaters have electrical controls to regulate water temperature and delivery; these draw about 5 W even when no hot water is called [9]. Domestic water heating systems might have a circulating pump to ensure immediate delivery of water to all taps in a building. Builders may find it more convenient – and cheaper—to install small electrical water heaters at remote taps. Some builders equip kitchens with a means of boosting hot water temperatures to over 90°C for hot beverages. Most designs include a small reservoir of hot water maintained at this temperature.

Many restrooms in commercial buildings are equipped with motion-activated faucets. The sensors and actuators are driven by mains power, ambient light, and batteries. These technologies are now appearing in residential faucets.

Communications and Information Technology Infrastructure

Builders of new homes are adding new communications and information technology products prior to occupancy. Wired systems are typically easier to install during construction. Many of the products are selected by owners after occupancy but the division of responsibility depends on local conditions and the specific requirements of the building. Builders must frequently install a communications network and the associated infrastructure to service the HVAC, safety, and security systems that now rely on wireless communication. Cable and satellite networks each require their own internal infrastructure of energy-using products [10]. Large parts of the eastern United States gain access to the Internet, video, and telephone service with fiber optic networks (FiOS). These homes use a FIOS converter box, which includes a rechargeable battery to maintain telephone service during power interruptions [11].

Mains outlets are now being offered with integrated USB and Ethernet connections. To date USB connections provide only power (and contain one power supply in each outlet); however, future designs will integrate power and communications.

Amenities and Features

Builders add features to their homes because customers want them. Many of these features involve energy-using products (some of which have already been discussed earlier). In the kitchen, builders often select and install the cooktop (or stove), in-sink garbage disposal, dishwasher and, less frequently, the refrigerator and oven. In some categories of homes, the builder installs of the major kitchen appliances. All of these appliances, except for the garbage disposal, are likely to have continuous—though low—power consumption when not being actively used. In the bathroom, heated towel racks are now common, though more in Europe than in North America. About 75% of Japanese homes have toilets with advanced, electrically operated features [12], including a heated seat, a “shower-wash”, and remote control. Each of those units will require a GFCI outlet nearby, too. New homes throughout the world are employing remote controls for lights, curtains, blinds, gas fireplaces, floor heating, and other amenities, all of which use power continuously.

Outside the home, in the yard, builders include all sorts of devices to make the yards more attractive and easier to maintain. Automated irrigation systems and low-voltage lighting systems are two common examples, both requiring continuous power for the power supplies and other components. Pumps and other equipment for swimming pools and spas will use several kilowatts intermittently while in active modes, but their timers, safety features, and demand controls draw much less power continuously.

Future homes will almost certainly be equipped with electric vehicle charging facilities (once these become standardized). In-home battery storage may also become common. Both will have fixed loads.

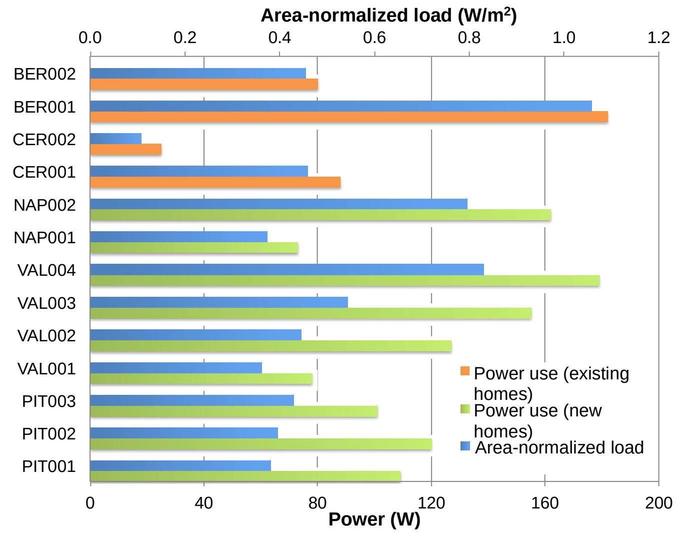
Measured Power Use of Unoccupied Homes

In order to better understand the aggregate impact of builder-installed loads, we measured the power use of new and existing unoccupied homes. This measurement is easy to perform on homes with advanced smart meters because they display the instantaneous power consumption roughly every 30 seconds. We located new homes that were recently completed by the builder but not yet occupied. We located vacant existing homes that were for sale. We inspected the home (where possible) and confirmed that all lights and other equipment—if any were present—were switched off. We then observed the meter for several minutes to verify that power consumption was constant. The floor areas, ages, and other characteristics were obtained from the builder or from a national real estate listing service (zillow.com).

We surveyed four existing and nine new homes in Northern California. The power consumptions are shown in Figure 2. The observed loads ranged from 25 – 180 W. The lowest value occurred in an existing home built during the 1970s, with no apparent upgrades since then. The highest values occurred in new homes and an existing home that had recently undergone a complete rehabilitation. Figure 2 also shows the observed loads normalized to their reported floor areas. Most of the homes had loads near 0.4 W/m^2.

This simple measurement protocol is susceptible to two kinds of errors, both of which lead to overestimates of builder-installed loads. First, the measurement will consistently over-estimate builder-installed loads because operating lights or other appliances may be overlooked. In at one new home, we later identified (though photo-documentation) outdoor lights operating during the measurement period. (We subtracted those loads.) Second, floor areas are consistently under-estimated from public records because owners fail to report home expansions and improvements. Actual builder-installed loads, per unit-area, will be lower than estimated until more reliable floor area data are applied.

Figure 2. Power measurements of unoccupied homes.

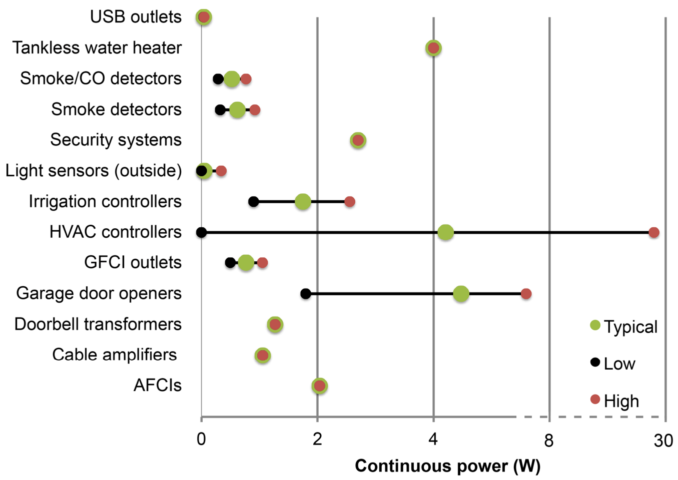


These measurements show that builder-installed loads are responsible for a significant fraction of total electricity use. New homes in our survey had an average of 120 W (1050 kWh/year) of builder-installed loads. This corresponds to about 13% of a single family home's electricity consumption in California – 7600 kWh/year [13]. We therefore sought to understand the causes of builder-installed loads through measurements of individual builder-installed products.

Power Use of Builder-Installed Products

We measured and compiled power measurements of builder-installed products from North America, Europe, Australia, and Japan. These are summarized in Figure 3. We focus on the lowest continuous power consumption of these products since this would occur even when the occupants are absent. For each product, we display the minimum and maximum reported values, along with our own estimate of a "typical" value.

Figure 3. Summary of measurements of builder-installed loads.



These measurements have numerous shortcomings. First, there is no clear definition of builder-installed products, so some products may also be consumer-installed. Second, sample size is small–sometimes only one product–and are therefore not representative. Third, measurement techniques were not standardized; they were typically instantaneous power measurements performed informally rather than based on, say, IEC 62301 [14] . Finally, the measurements are often imprecise because most metering equipment is not accurate at the very low power consumption of these products (below ~2 W).

Most of these builder-installed products consume very little power--often less than one watt--which translates into very little annual electricity consumption. (One watt of continuous power use corresponds to 9 kWh per year.) The number of these products present in a home may be quite large, however. A modern American home could easily contain eight GFCI circuits in order to comply with safety codes. Similarly, a new home will require at least five smoke detectors (though this depends on number of rooms and floors). This situation also occurs with respect to various remote-controlled devices and perhaps, in the future, USB outlets. The aggregate load of these products will add up to over 75 W in most new homes. Table 3 is a sample tabulation.

Table 3. Tabulation of builder-installed loads in a typical new U.S. home.

Components	Power (W)*
7 AFCI	14.3
8 GFCI outlets	6.2
4 Smoke detectors	2.5
4 Smoke/CO detectors	2.1
Built-in microwave oven	1.0
Built-in oven	2.0
Built-in Dishwasher	1.5
Cable Amplifier	1.1
2 Ceiling fan controllers	2.0
Doorbell transformer	1.3
Garage door opener	4.5
HVAC controller	25.0
Irrigation controller	1.8
2 Light sensors (outside)	0.1
9 Occupancy sensors	3.8
Security System	4.5
Tankless water heater	4.0
USB outlets	0.2
Total	**77.8**

*Some values are estimated

This list includes many of the most common devices, but it could be much larger if the builder is responsible for more built-in appliances or the home has continuous ventilation, a heat pump crankcase heater, or other small heating devices. Nevertheless, these listed loads alone translate into over 650 kWh/year, or about 9% of the electricity use of an average California single-family home. New products may have significant standby power use. For example, electric vehicle chargers will draw 1 – 13 W, depending on manufacturer and configuration at the time of measurement [15].

Energy Saving Opportunities

Reducing the energy use of builder-installed loads would appear to be difficult because nearly all of these components draw very little power. However, several strategies are possible, including:

- Identification of lowest-power solutions when a range of power consumptions are available
- “daisy-chaining” GFCIs, allowing one circuit to serve many outlets (this is already done)
- more efficient circuitry and power management
- a separate DC circuit to serve DC-powered appliances
- use of energy-scavenging sensors and controls in place of grid-powered components

The solutions must be very inexpensive because the value of the savings will be small. It is possible that non-energy benefits, such as safety during power outages, will drive the decisions.

One way to stimulate attention to builder-installed loads, possibly leading to energy savings, is to establish a protocol to define and measure builder-installed loads. This measurement would be publicized and become a sales feature for new, low-energy homes. In the future, authorities might establish a cap on builder-installed loads.

Conclusion

The miscellaneous loads represent a growing fraction of residential electricity use. They are challenging to define, measure, and reduce. The “builder-installed” loads, and especially those with continuous power draws, make up a special category because they are selected by a single entity and installed at more or less the same time. The builder installs these loads in order to satisfy safety codes, provide security, support basic building services, and provide features that attract potential buyers. A typical home can have 50 builder-installed components that draw power continuously.

Only a few measurements of builder-installed loads in completed homes have been performed but these are sufficient to indicate their power consumption is significant. Measured power consumptions of the individual components are sparse. In addition, the measurements have been performed in variable conditions over the past decade. Nevertheless, it is possible to construct an inventory and estimate total power draw. In even simple cases, the loads approach 80 W of continuous power, or over 650 kWh/year. This corresponds to 9% of an average American home’s electricity use, but much more of a low-energy home. The types of products and power consumption may be different in Europe or Japan.

Reducing builder-installed loads is technically and economically challenging. Nevertheless, several technical strategies deserve investigation. These may also provide side-benefits, which, ultimately, may make lower loads caused by builder-installed components possible. The appliances and components installed by builders in new homes are extraordinarily diverse; however, they might be addressed by a single comprehensive strategy aimed at contractors and the home-building sector. Furthermore, many regions already have energy codes addressing construction of new homes, so regulatory, informational, and financial pathways to promote low energy already exist.

Acknowledgments

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Table 2. List of builder-installed devices that draw power continuously.

Table 2a. Components required for safety reasons.

GFCI outlets
GFCI breaker
AFCI
Smoke detector/alarms
Smoke/CO detector

Table 2b. Components installed to provide occupant security.

Entryway audio and video systems
Security systems
Doorbells
Garage door opener
DC exterior lighting power supply
Electronic door locks
Motion/light sensors

Table 2c. Associated with heating, cooling, ventilation, hot water

Demand water heater (for gas) controls
HVAC controls
In-sink heater
Ventilation fans
Well pump
Heat pump crankcase heater
Minisplit ACs
Ceiling fan remote controls
Hot water circulation pumps
Boiler circulation pumps
Motion-activated faucet sensors

Table 2d. Communications infrastructure

Cable amplifier
Telephone/Internet box
FIOS boxes
Intercoms
Wifi router
Ethernet hub

Table 2e. Amenities and features

Irrigation/sprinkler controls
Vacuum cleaner (built-in)
Gas fireplace remote
Remote controls for blinds and curtains
Oven/stovetop
USB outlets
Pool pumps
Fountains
Toilet flush sensor
Smart toilet
Dishwasher
Heated towel racks
Inverters for photovoltaic systems
Sump pumps
Electric vehicle chargers

Smart home – good things come to those who wait?!

Eva Harms

GfK Retail and Technology GmbH

Abstract

Smart home is not a completely new concept. There have already been solutions for home automation based on bus networks in the beginnings of the 21st century. However, none of them have become prevalent and really gained interest from the mass market.

Now, ten to fifteen years later, the smart home market is gaining traction. But what has changed since then? One aspect is certainly the dominant presence of the smartphone and the user's willingness to take the device everywhere and to also use it for a broad range of other functionalities – apart from calling and texting – one of them being home automation.

As brands from traditionally separate industries clash in their search for the most lucrative product or service, they are under significant pressure to innovate and define their niche in this sprawling cross-sector market. While the smart home is capturing the imagination of consumers, brands face the challenge of communicating product benefits effectively and gaining the trust of consumers in an increasingly prominent yet complex marketplace.

Nevertheless, a lot of questions arise: has the smart home market really become a mass market yet? What kind of different product areas gain interest from consumers and what kind of products do they actually buy?

A deeper insight into three key countries of the European smart home market[1] will help to understand the current development of this complex market. Data from GfK Retail and Technology's point of sales panel will provide first insights to answer these questions.

[1] If nothing different is stated, all data mentioned hereafter is based on market sales out data audited within the point of sales panel by GfK Retail and Technology in these three selected European countries: DE, FR, GB.

Introduction

A promising market

The smart home market is a very promising market. Industry experts may predict different numbers, but they all agree on the vast potential that this market holds. Deloitte, together with BITKOM, the German federal association for IT, Telecommunication and New Media, predicts that in 2018 there could already be one million smart-home-households in Germany (progressive scenario). Even with a conservative estimation this number could already be reached in 2020.

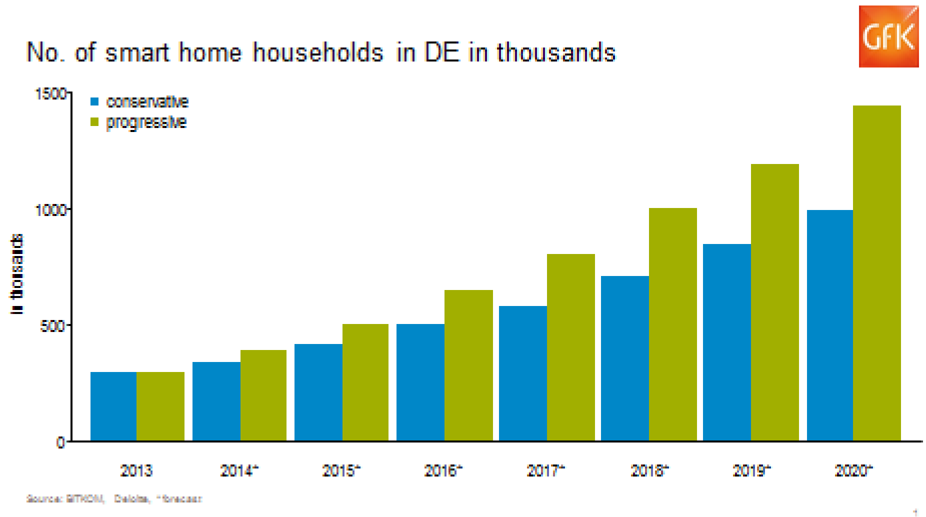

Figure 1: Number of smart home households in Germany in thousands

Figure source: BITKOM

What is a "smart home"?

The term "smart home" has many definitions and synonyms. Use cases range from the classical controlling of garage doors and smart alarm systems over connected audio home systems to pre-heating the oven and starting the robot lawnmower. It is therefore all the more important to create clear distinctions for GfK's tracking of smart devices within its point of sales panel.

GfK Retail and Technology defines a smart home as a home that includes different functions and devices that are connected in an intelligent network. This way, the user can interact with these devices and functions with a mobile device (smartphone/tablet). Within this communication, GfK includes three different types of interaction:

- Remote status check: the user can request information about the status of a certain device on to a mobile device, e.g. check whether windows are open/closed
- Remote information: the device sends unrequested information to the mobile device, e.g. in case of an emergency, e.g. the smoke detector sends an alert in case of fire
- Remote control: the user can send a control request to the device via a mobile device in order to change a certain status of it, e.g. start the program of the washing machine

Devices that fulfill at least one of the scenarios listed above are counted as "smart" within GfK Retail and Technology's point of sales panel[2]. Sales of such models will consequently be included in GfK's smart home reporting.

[2] Included are also smart major domestic appliances with a smart diagnosis function.

Methodological annotation

All figures regarding sales volume, value or price mentioned in this paper are based on the international GfK Retail and Technology point of sales panel. Data from this point of sales panel show retail sales out information including volume, value, price, etc. for defined product groups. Figures from the point of sales panel show representative sales out information for the channels covered, which – depending on the respective country and GfK product group - account for 50% to 98% of the total market.

GfK Retail and Technology monitors sales of smart devices from 36 GfK product groups. Sales of smart devices are being separated from sales of “traditional” items and then merged in a fusion reporting of only smart items. These 36 product groups are clustered to five categories referring to different smart home areas. These categories are: Home Automation and Security, Smart Entertainment, Smart Major Domestic Appliances, Smart Small Domestic Appliances and Communication and Control Devices (routers, gateways, smart plugs).

What are essential preconditions for a smart home?

A high internet penetration is the basis for a smart home

Home internet access is one of the most important preconditions for the success of smart home. A large amount of smart home systems are connected in an intelligent network based on the internet. These devices are then connected to a gateway which enables communication with the internet router. Hence, devices can also be controlled or monitored from outside the home via internet.

In Europe, internet penetration is already relatively high. In 2014, 90% of all British have had internet access, while in 2000 it was only one quarter that could use the internet. Taking a closer look at the German market, it reveals a similar picture: 89% of the population in 2014 had access to the internet – in 2000 the number was only at 28%. France, however, slightly lags behind, with a current internet penetration of 83% and a former level in 2000 of 13%. Nevertheless, the vast majority of inhabitants of EU3 have internet access, providing them with the opportunity to integrate smart home systems to their homes.

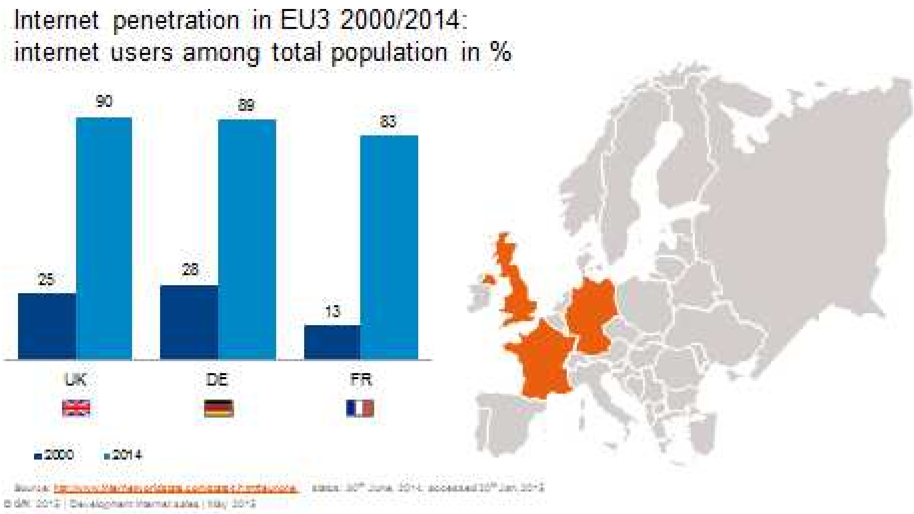

Figure 2: Internet penetration in France, Germany and UK, (2000/2014)

Figure source: Internet World Stats – Usage and Population Statistics

Booming smartphone sales facilitate increasing usage of smart home systems

In the first half year of 2015, 24.27 million smartphones have been sold in Germany, France and Great Britain. In the same period of last year, the total volume in EU3 amounted to 22.36 million devices, showing a growth rate of 8.5%. Within EU3, Germany is the largest market accounting for 46% of the total volume in HY1 2015. Great Britain comes second with a total sales volume of 8.8 million devices in the first half year of 2015. France ranks third, with volume sales of 4.4 million smartphones and the highest growth rate among these three countries – 27.9%.

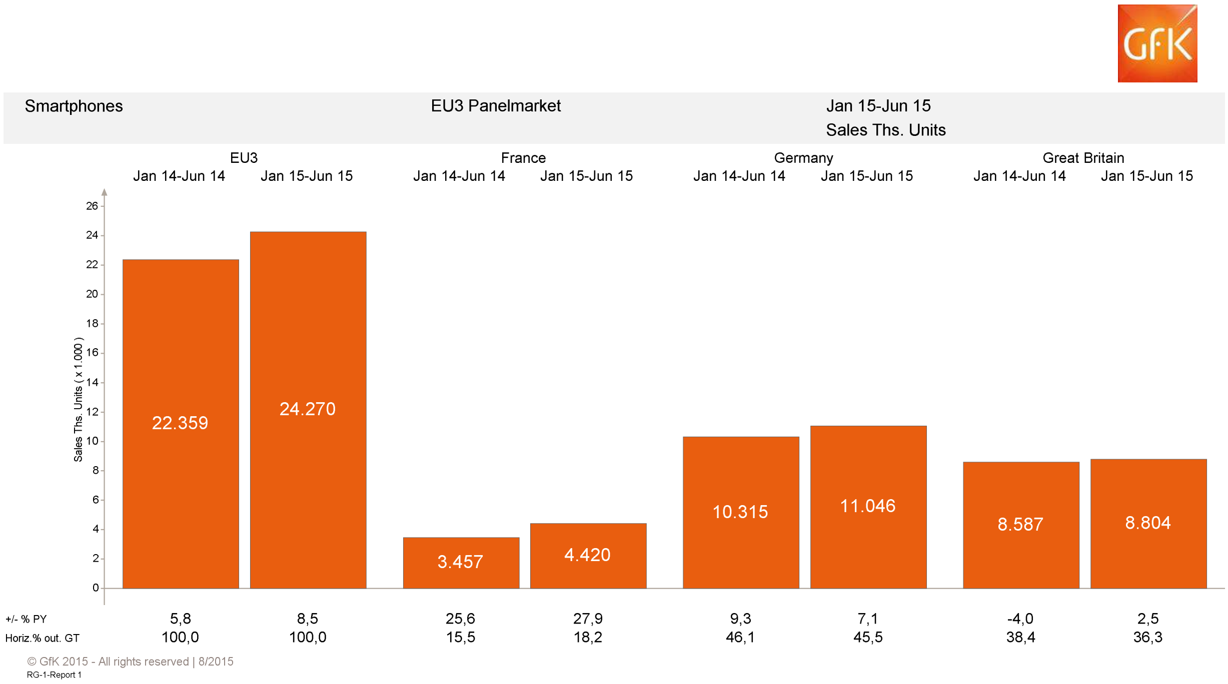

Figure 3: Volume sales of smartphones in France, Germany and UK, (HY1 2014/HY1 2015)

Figure source: GfK Retail and Technology point of sales panel

Increased awareness of smart home and promotion of clear benefits

The topic of smart homes has not yet reached the masses. According to a consumer study 72% of German households have never before heard of smart home or do not know any details[3]. To create a joined up smart home, the market needs joined up concepts and joined up products. Hence, market players, industry and retailers, need to collaborate to create awareness of smart home and to communicate the features, but especially, the benefits of these systems.

Unified transmission standards and knowledge of energy consumption

One of the major challenges for the smart home field lies in the fact that there is no unified transmission standard that allows all the different isolated solutions to work together. This prevents skeptical users once more from investing in a smart home, as future interoperability of different devices is not guaranteed. Thus, industry associations with leading players from the technology, home automation and domestic appliances field are working on integrated solutions that allow the joined usage of different solutions and products.

Related to this challenge is also the question on how much energy the different technologies and smart devices actually use. Is it really worth to invest in smart appliances that are supposed to save energy? Or do these devices and the technology that lies behind actually consume more energy? These are questions that potential users ask themselves. Most certainly they will not buy any smart home devices unless there is a balance between the saved energy and the energy consumption of the smart electrical devices. Especially relevant is the power demand of the smart home technology. As WiFi is designed to transmit high data rates power demand is relatively high. In contrast, ZigBee only needs to transmit little data rates for easier home automation commands and thus energy demand is much less than for WiFi. An energy label for such devices might silence such scruples.

[3] GfK Consumer Study 2014 „The future of Smart Home"

Current development of the smart home market

General overview

At this stage of the development cycle, it is important to understand which functionalities of the smart home market are of most interest to consumers and what kind of products they actually purchase. With its point of sales panel, GfK Retail and Technology is able to exactly measure how the smart home market is developing and what kind of smart products are being sold.

In the first half year of 2015, sales of smart models have amounted to almost 7 million units in EU3.[4] Smart Entertainment leads the way in unit sales, followed by Communication and Control Devices and then Home Automation and Security and Smart Major and Small Domestic Appliances in much smaller quantities. The latter still only plays a minor role within the smart home market. It might come surprisingly that growth rates of the smart home market for the first half year of 2015 are not very high – with an average of 0.1% for EU3 and 1.9% for France and an even negative growth of -2.0% for the UK. These relatively stable growth rates are due to the high share of smart entertainment, which itself is relatively stable or even declining as in France and Germany. As for the absolute sales per county, Germany is leading in terms of units sold with 4 million smart devices in HY1 2015, followed by the UK with 1.8 million units and France with 1.1 million units.

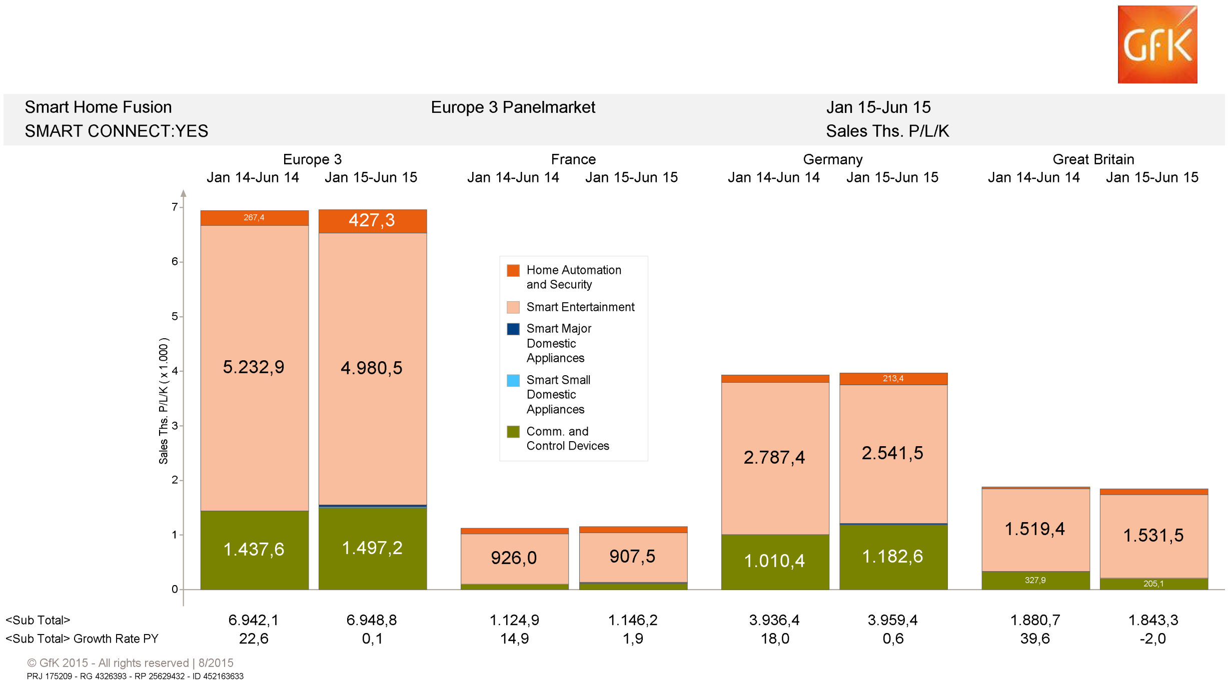

Figure 3: Volume sales of smart home categories in France, Germany and UK, (HY1 2014/HY1 2015)

Figure source: GfK Retail and Technology point of sales panel

[4] Not all 36 product groups that are part of GfK's smart home fusion reporting are tracked in all of the three countries. Sales of different countries can thus not be compared one to one.

Sales of smart devices mainly come from sales of TVs. These devices are not only Smart TVs in the sense of that they have access to the internet, but they also fulfill GfK's criteria of a smart product, meaning that they can be controlled remotely with a mobile device. The second most important product group in EU3 in June 2015 according to sales volume is Comm. Devices. These devices are gateways and smart home hubs, working as transmitter boxes between smart home sensors and the router and smart plugs. Devices referring to the classical home automation, like alert detectors and security and lighting systems still show little sales, as do smart major and small domestic appliances.

Obviously, the smart home market is a seasonal market, with increasing sales especially during the Christmas period. This is mainly due to the high weight of Smart Entertainment and the high seasonality of entertainment products no matter if they are smart or not. This also explains the negative growth rate of -12.5% in June 2015 for EU3, while smart TVs are even declining at -25%.

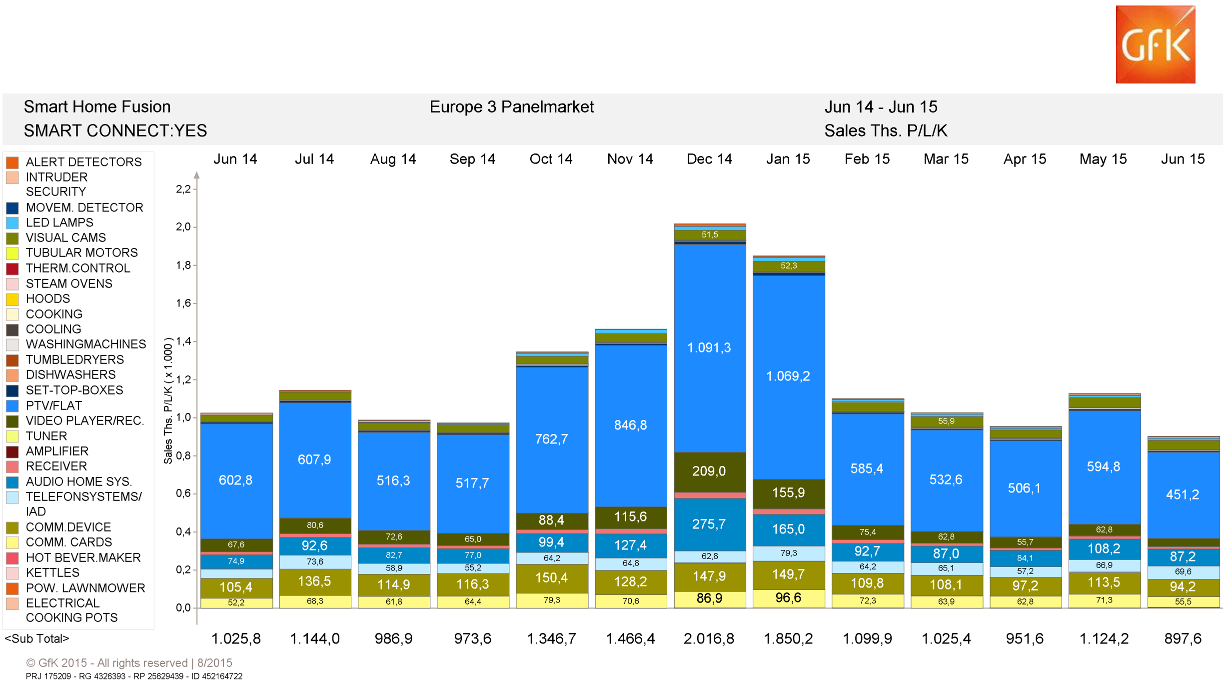

Figure 4: Volume sales of smart home product groups in EU3, (June 2014-June 2015)

Figure source: GfK Retail and Technology point of sales panel

Closer look at Home Automation and Security

Sales of the category Home Automation and Security have amounted to 68300 units in June 2015. This means that the category has grown at 41.7% compared to the last year's period. When analyzing more thoroughly the development of these "classical" home automation items, it becomes clear that visual cams, such as net cams, account for the majority of the sales volume. Users see a real benefit behind cameras that can be observed or whose direction can be changed remotely. Nevertheless, in the past months, other smart devices within that category have gained importance: LED lamps, lighting devices whose color or lighting intensity can be changed via a mobile device, show increasing sales. This use case aims at the increased comfort the user gains with using smart devices.

Another benefit that consumers expect from a smart home is an increased sense of security. In GfK's point of sales panel this goal is reflected in sales of smart alert detectors, like smoke or water detectors and devices coming from the product group intruder security, namely alarms, window and door sensors. Smart movement detectors, smart tubular motors – used for controlling electric awnings and shutters – and smart thermostats still only play a minor role within this category[5].

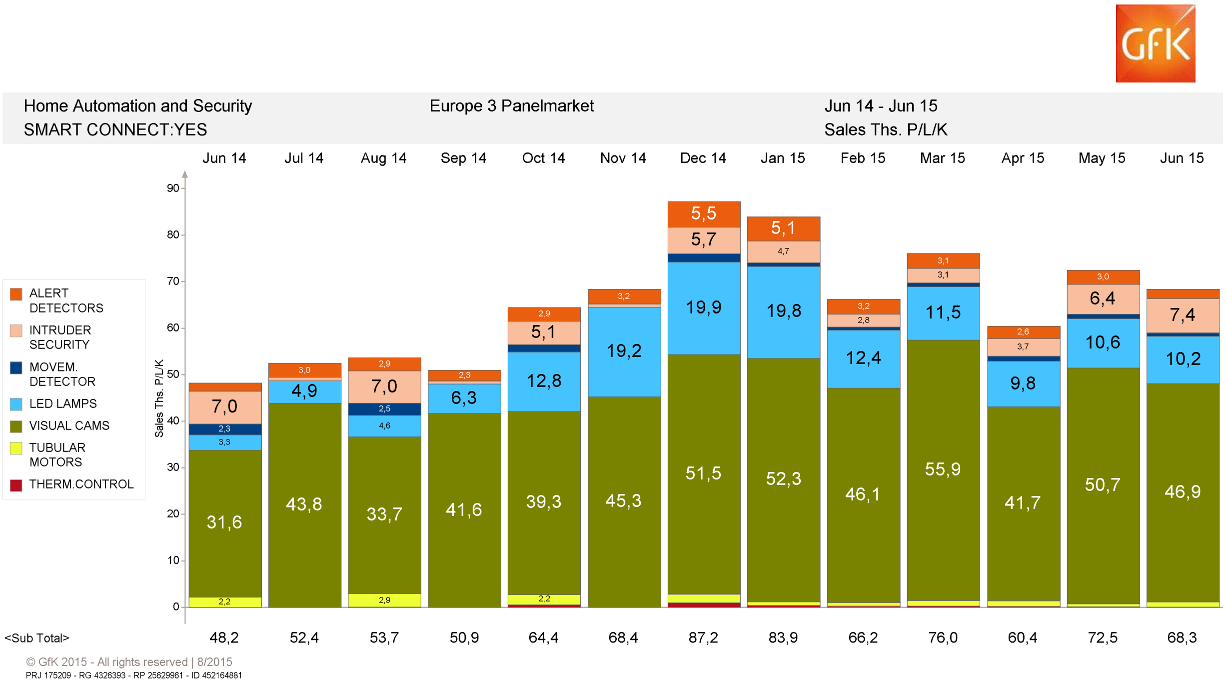

Figure 5: Volume sales of product groups from the category Home Automation and Security in EU3, (June 2014-June 2015)

Figure source: GfK Retail and Technology point of sales panel

Thorough analysis of Smart Major Domestic Appliances

Development of the category Smart Major Domestic Appliances

Although major domestic appliances do not play a primary role within the Smart Home field yet, there have been a lot of innovation and newly launched products on the market. Apart from smart devices according to GfK's definition, there are a number of items that are rather smart-prepared, as they need the additional integration of certain communication modules in order to function as a smart device. Within GfK these items are classified as "smart-prepared" and, as they are not smart ex works, not coded as "smart" according to the earlier mentioned definition and hence not included in the already shown analyses. In order to give a clear view of the smart and smart-prepared market within major domestic appliances, the following analyses will be based on sales of smart and smart-prepared models.

Sales of smart and smart-prepared major domestic appliances still do not show volumes as high as other product groups within the smart home market. Nevertheless, the development of the last months is considerable. While in June 2014 only 6300 units of smart/smart-prepared items have been sold, in the same month of this year, sales have amounted to almost 14700 units. Smart washing machines, devices including features to start washing programs, lead sales of smart major domestic appliances. Second most important product group are refrigerators (cooling): most of these smart devices include the so called smart diagnosis functionality. This allows the user to diagnose problems by transmitting information to the customer service either over the phone or via an app. Besides actual sales, also the number of the different smart product groups has increased – smart/smart-prepared dishwashers,

[5] Product groups Movement Detectors and Therm. Controls only audited every second month in 2014.

freezers and even wine cabinets have been launched – meaning that there has been a lot of innovation lately within the smart major domestic appliances field.

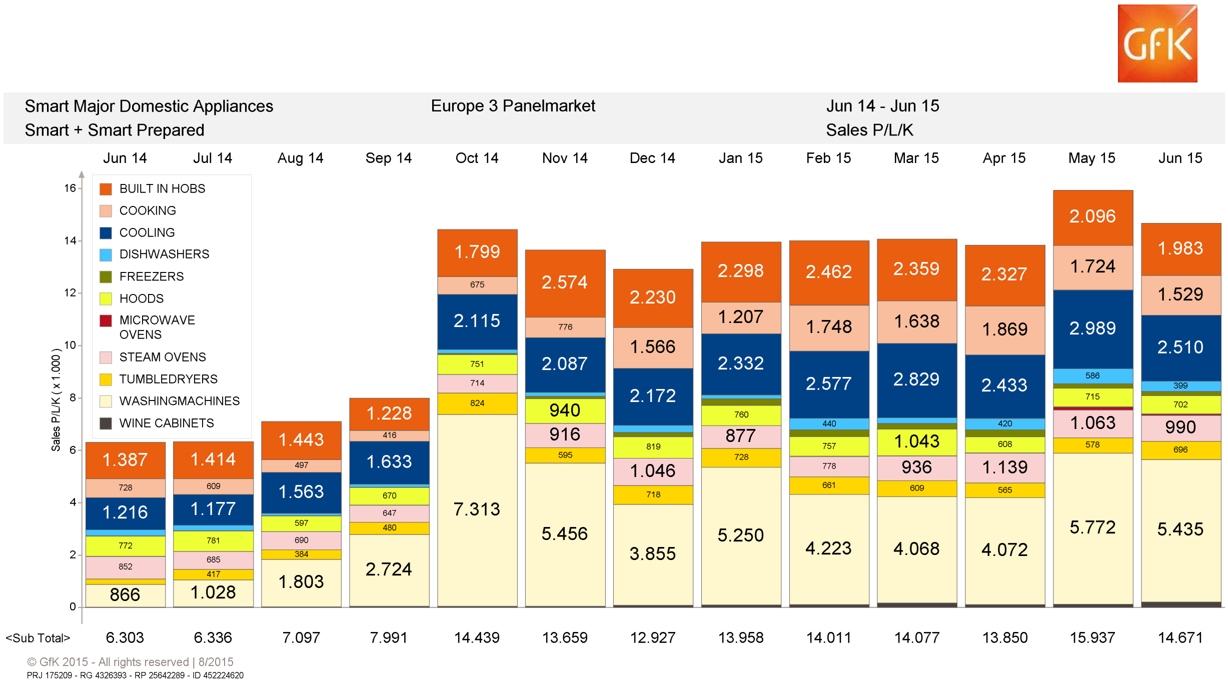

Figure 6: Volume sales of product groups from category Smart Major Domestic Appliances in EU3, (June 2014-June 2015)

Figure source: GfK Retail and Technology point of sales panel

Another proof of innovation is the fact that both the number of different selling brands and different selling items within smart and smart prepared major domestic appliances have increased since the last six months. While in January only five brands have been selling 173 different items, in June 2015 one more brand has launched smart/smart prepared items, amounting 218 in total.

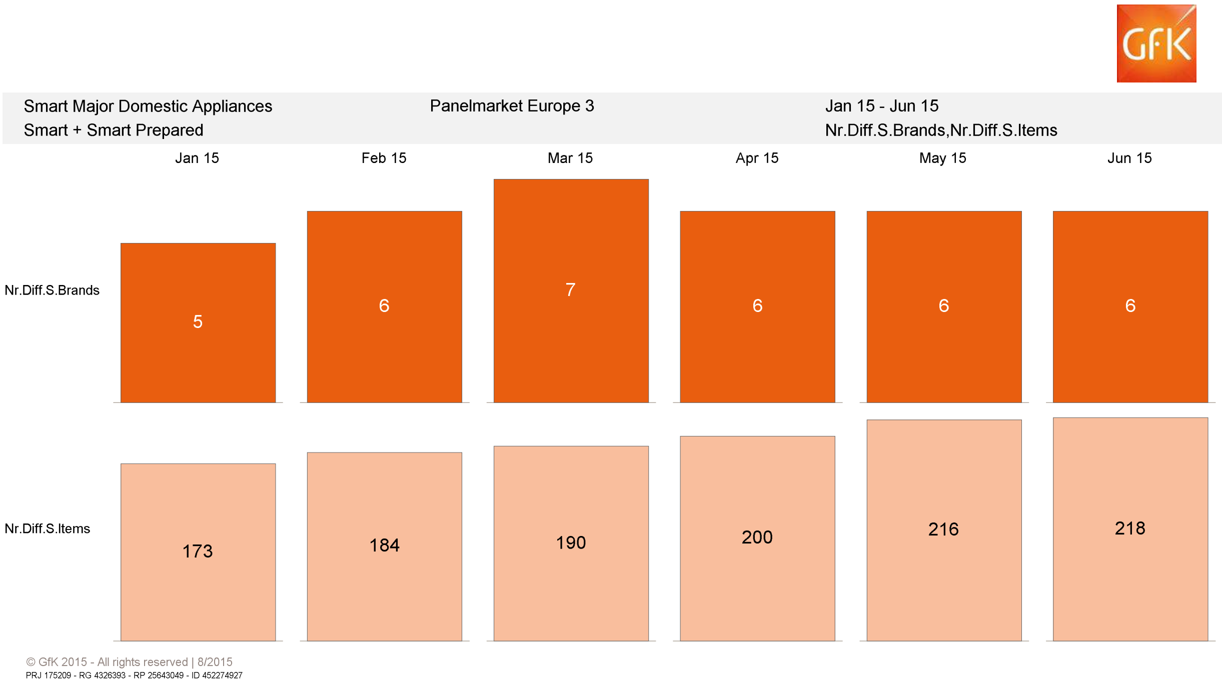

Figure 7: Number of different selling brands and items for the category Smart Major Domestic Appliances in EU3, (January 2015-June 2015)

Figure source: GfK Retail and Technology point of sales panel

Price analysis within the category Smart Major Domestic Appliances

Especially for major domestic appliances, prices between smart/smart prepared and traditional models vary considerably. Hence, a significant price premium can be achieved with the smart items. The illustration below depicts the average sales price of smart/smart prepared and traditional models for the top five manufacturers of the category. For wine cabinets, with an average price difference of €2189, the absolute price premium of smart models is the highest. But also for the other product groups, the average sales price of smart items is higher than for traditional models with an average price premium of €825 for the total category.

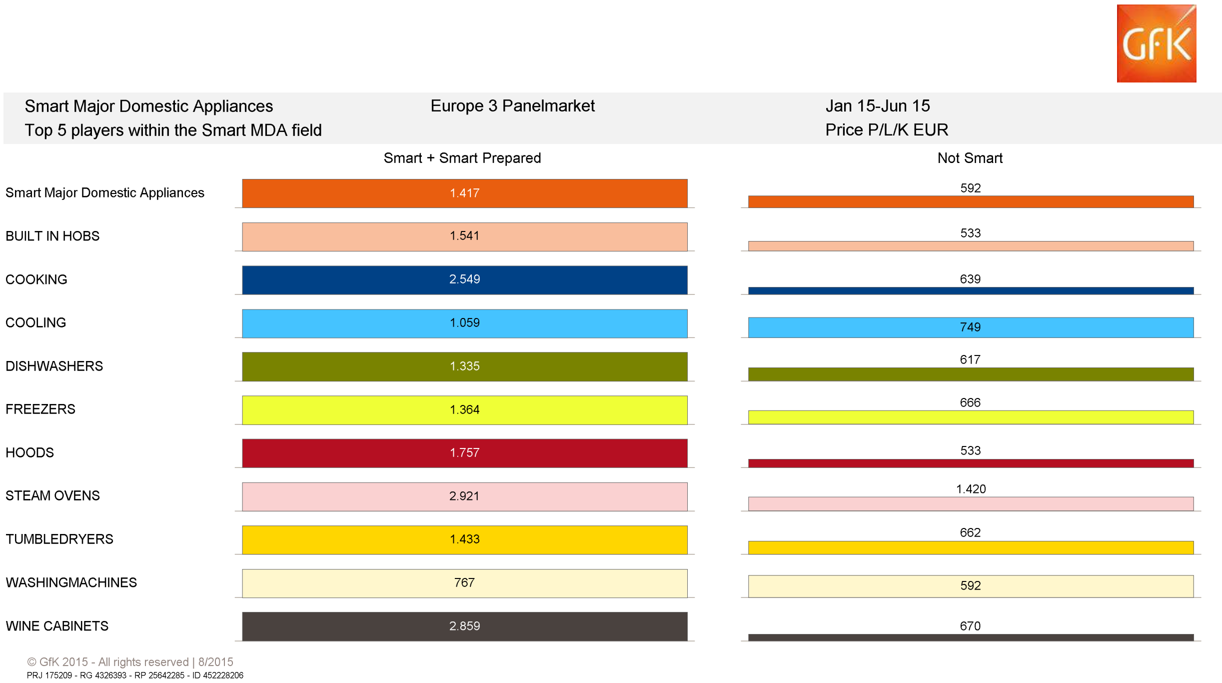

Figure 8: Price comparison of smart items and traditional items in EU3, (HY1 2015)

Figure source: GfK Retail and Technology point of sales panel

Nevertheless, it is pivotal to keep in mind that smart and smart prepared devices still only represent a small percentage within the major domestic appliances field. In the first half year of 2015, 0.2% of sold units and 0.43% of the total MDA value sales in EU3 have been made with smart models, while the share of smart prepared devices amounted to 0.2% (units) and 1.0% (value).

Outlook

In any case, with prominent and international players like Samsung, Google and Apple, pushing into that promising market and announcing ambitious goals concerning the interconnection of their products, the Smart Home market is on a good way. But also the number of smaller start-ups, positioning themselves in a niche of the broad smart home market, is increasing and thus giving the market a further boost.

Furthermore, parallel emerging categories like connected cars, wearables, connected health and Ambient Assistant Living will become more and more significant and help to raise awareness for connected devices, as well. As for connectable personal care products like blood pressure monitors and electronic personal scales, GfK measures increasing shares, especially in terms of value sales, of connectable devices in Germany, France and Great Britain. This shows that there is an increasing interest also for such innovative consumer products.

Conclusion

It has become clear that manufacturers from a broad range of different industries try to position themselves in the promising smart home market. Thanks to the high internet penetration and the public's familiarity with mobile devices, two pivotal foundations for smart home are already in place. Besides, similar emerging categories are attracting consumers' interest and thus boosting interest in Smart Home, as well. However, there is still potential in increasing awareness of smart home solutions and its benefits and in creating interoperable transmission standards that only consume little energy.

Sales data from GfK Retail and Technology's point of sales panel have shown increasing sales for the smart home market. Smart Entertainment is leading in terms of sold units, followed by communication and control devices. Classical home automation and security products and smart domestic appliances are still on a lower level when it comes to actual sales, but increasing in importance.

References

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[2] http://www.internetworldstats.com/stats4.htm#europe.

A Survey of Power Supply and Lighting Patterns in North Central Nigeria- The Energy Saving Potentials through Efficient Lighting Systems

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Abstract

While power crises persist in Africa with many heads of governments placing priority on power generation, the need for energy conservation through efficient lighting can be a short-term solution. This paper compiles the power supply and consumption pattern of lighting of six cities and towns in North Central Nigeria. A total of 1,637 residential households were surveyed. Each compound had 2 to 4 houses. Most of the households surveyed had a combination of modern and local buildings such as huts. The work revealed that the predominant electricity consumption is in lighting. Electricity supply is found to last for an average of 5 days a week and 9.8 hours a day. The major electric lighting source is the 60W and 100W incandescent bulbs, but a significant population uses both incandescent and energy efficient lamps (e.g. compact fluorescent lamps, CFLs) for their lighting needs. In the absence of public power supply, kerosene and low power generators are used as alternative sources for lighting. The number of kerosene lamps in a residential compound was found to be 3 or more. About 70% of power generated in Nigeria can be saved if efficient lighting sources such as CFLs and solid state lighting are urgently adapted. Also, an estimated 796.4 billion naira (US$4.98 billion) will be saved annually from fuel to power electric generators if they are replaced by solar- based lighting.

Key words: Lighting, power, generators, incandescent, fluorescent, solid state

Introduction

Lighting is an indispensable energy end use that is required to perform all tasks efficiently. Electric lighting on the other hand represents the most efficient form of artificial lighting source. However, in Nigeria like most sub-Saharan African countries, electric lighting is hampered by inadequate electricity generation and supply. Nigeria's electricity demand is in the range of 20,000 MW to 25,000 MW [1]. The current nominal electricity generation capacity is less than 6,000 MW [2] with the actual electricity generated fluctuating between 2,950 MW to below 4,000 MW [3]. This enormous shortfall in electricity production is further exacerbated by high losses due to inefficient distribution system [4], hence the frequent power outages experienced by consumers. Frequent power outages affects everyone: students cannot read at their desired times because of the fear for power failure; households and business owners are forced to look for alternative power supply to meet their lighting needs, hence the prevalence of small generators popularly called "I pass my neighbor" in Nigeria's small to medium income households. For high income households, diesel generators are used for lighting and other domestic appliances such as air conditioners, refrigerators, electric iron, etc. Beside huge income loss, generators are a source of stress (or fatigue) and health hazard as a result of the noise generated and the greenhouse gas emissions [5]. It has been reported that Nigeria spends an estimated sum of 796.4 billion naira, (US$4.28 billion equivalent) annually on fuel to power electric generators [6]. This huge expenditure on small power generators has a toll on the gross domestic product (GDP) growth of a nation whose per capita income is among the poorest globally.

Electricity consumption in Nigeria has been reported to be dominated by the residential sector [5], of which lighting is a major contributor. Unfortunately, inefficient lighting sources such as the incandescent bulbs are generally common. Every household is adorned with incandescent bulbs. These lamps waste 95% of their input energy as heat and barely convert 5% of the energy to light. Besides the use of inefficient electric lighting bulbs, efficient utilization of available power by the end users is also lacking; it is not uncommon for electric lamps to be left on (glowing) when their light are not needed, e.g. during day light hours in homes, offices and commercial centers. With a population of more than 10 million people having access to electricity in Nigeria, there is a potential of saving large amount of electricity generated for other productive uses if efficient lighting technologies are adopted [7,8].

The Nigerian government's efforts towards solving the energy crises in the country has always been in the direction of building more power plants and the unbundling of agencies (National Electric Power Authority, NEPA in 2005 and the Power Holding Corporation of Nigeria, PHCN in 2013) responsible for power generation, transmission and distribution. Despite this efforts and the huge amount of money invested into the power sector, electricity generation has remained below 4,000 MW on the average. If the solution to electric power problem in the short term is not diversified to include electricity end users efficiency such as utilization of efficient lighting technologies, the quest for adequate and stable power supply would continue to elude the nation. Apart from the fact that efficient utilization of electricity means more power available to other productive and extended uses, it is also capable of substantially reducing materials waste and greenhouse gas emissions. This paper presents the result of a survey carried out in North Central Nigeria on household electric lighting energy consumption. The contribution of this work comes about as the result of Nigeria's first attempt to evaluate energy savings opportunities from lighting by community households. In addition, this work would provide a framework for government to develop sustainable policies and programs on the efficient electricity utilization in the country, particularly in the area of efficient lighting systems.

Methodology

The survey method includes the use of household questionnaires, interview with key informants (especially heads of households or their representatives), physical observations of different kinds of light fixtures and a review of existing documents from relevant agencies such as the National Population Commission (NPC) and the National Bureau of Statistics (NBS). Samples of 1,637 households were surveyed based on the 2006 national population census results. The study was conducted in six local government areas of Benue State and one local council in Abuja (Federal Capital Territory, FCT). The questionnaires were administered orally to randomly selected households in the various wards that make up the towns by enumerators who filled out the questionnaires during the interview. The enumerators carried with them samples of electric light bulbs to the respondents. In households where access was granted the enumerators counted the bulbs themselves and determined their types. The data collected were subjected to statistical analysis using appropriate statistical packages, such as SPSS and Excel.

Table 1 compares the lumen output of CFLs, LEDs and incandescent lamps. Using the information in Table 1 and Table 2, the total energy consumption by each lighting source was estimated using the modified top-down approach reported by Gifford *et al*, [9]:

$$E_i = P_r txnN \qquad 1$$

where,

E_i = Average energy consumption for a given lamp type

P_r = watts of bulb

t = duration for which the bulbs were left glowing in hours

x = Percentage of population the use the type of lighting

n = the population sampled

N = number of days with electricity in a year

As an example, using equation (1) and information in Table 1 and Table 2, consider that a 60W incandescent bulb is replaced by a higher lumen output light such as an 18W CFL. The energy consumed (E_1) by the 60W bulb per year for lighting is 978 kWh, while the 18W CFL will consume 294 kWh energy (E_2) within the same period. The energy saving potential ϕ is calculated using equation (2):

$$\phi = \left(1 - \frac{E_2}{E_1}\right) \times 100\% \qquad 2$$

$$\phi = \left(1 - \frac{294}{978}\right) \times 100\% = 69.9\%$$

Therefore, replacing a 60W incandescent bulb with an energy efficient CFL will save 69.9% of electrical energy from lighting alone. A similar method was employed to estimate the potential energy savings from lighting in the surveyed areas, North Central Nigeria and the entire country using the data generated from this research and others obtained from National Bureau of Statistics (NBS), [8].

Table 1: Power rating of various bulbs according to their lumen [10]

Lumen (lm)	Incandescent (W)	CFL (W)	LED (W)
>5,000	-	80 - 100	-
2,600	150	32 – 35	25 – 28
1,600	100	23 – 26	16 – 20
1,100	75	18 – 22	13
800	60	13 – 15	8 – 12.5
450	40	9 - 11	6 – 9

Results and Discussion

The number of hours electricity is supplied to households in the surveyed areas is shown in Table 2. The result shows that electricity supply range from 4 to 12 hours with an average of 9.8 hours per day. This value is slightly higher than the number of lighting hours reported by CERDC in 2009 which may perhaps be due to a slight improvement in power generation and distribution by successive governments. However, no household received an uninterrupted power supply for a whole day. Investigations also revealed that electricity supply is often rationed and that there is no guarantee that there would be constant power supply during the rationed period. The worst affected town is Gboko were electricity supply lasts for only between one and four hours per day.

Table 2: The number of incandescent bulbs per household, days with electricity per week and hours with electricity per day

Area	Ave. No. of Incandescent lamps per household	Ave. No. of days with electricity per week	Ave. no. of hours with electricity per day
Gboko	3.8	2	4
Karu (FCT)	3.5	7	12
Kwande	18.0	4	8
Makurdi	2.5	4	14
Otukpo	2.5	7	10
Vandeikya	7.8	6	11
Total Average	**6.4**	**5**	**9.8**

On the number of days electricity is supplied to the selected study areas, it is clear from Table 2 that Otukpo and Karu (FCT) receive electricity supply daily while Gboko, Kwande and Makurdi receive an average electricity supply of two – four days per week. The electricity supplied in these towns/cities is mostly rationed due to the use of old transformers or overloading of the existing transformers [11]. It is common to have a large cluster of residence that is fed from a single transformer of low power rating. Gboko is again the town that is the worst affected.

Despite the power challenges the government has not found it expedient to bring up policies that would curb power wastages through the use of energy efficient technologies. Figure 1 shows a breakdown of lighting types by regions, and that incandescent bulbs are most commonly used, i.e. by 40.8% of respondents. A good proportion of respondents (44.7%) also use both energy efficient lamps (EELs) such as compact fluorescent lamps (CFLs)/fluorescent, and incandescent lamps (Fig. 1). This result is consistent with the report by CREDC [12]. There is no definite pattern from Fig. 1 that suggests whether or not awareness of the energy efficiency of lighting sources was responsible for the choice respondents made. For example, a large proportion of respondents (55.8%) in Makurdi, the capital city of Benue state use only incandescent bulbs for their lighting needs. This study also revealed the incandescent lamps in use are rated at 60W, 100W and 200W. Of these, 60 and 100W are the most commonly used, and the choice between these two is a matter of availability (their costs are about the same, i.e. ₦40.00), and a function of the household's mains current level which in most cases varies depending on how close the household is to the transformer or what size of the transmission wire was used. Those who live in traditional hut structures are not allowed to connect to the national grid system. Therefore, in order to have access to the public power supply, they obtain electricity from their neighbors using the 1.5 mm copper wire which are often buried under ground. These wires leak current to the ground thereby creating low shielding to adjacent households.

There is significant increase in the use of energy efficient lighting technologies among households in Oturkpo (10%), Kwande (17.6%), Gboko (20.8%) and Karu (31.7%) towns unlike Vandeiky (1.1%) and Makurdi (6.0%) towns. The primary reason has been the high lumen output otherwise known as "brightness" of these EELs when compared to incandescent bulbs especially in the face of low power supply voltage from the national grid. Unfortunately, the power ratings of the common EELs in use are high (40 and 80 Watts), though; 18W and 24W CFLs are also available. The use of higher power rated EELs is aimed at achieving higher “brightness” under low power/voltage situations. Other factors that have discouraged the rapid deployment of EELs are the lifespan and high cost per lamp. Although it is expected that EELs should have 4 times the average lifespan of incandescent bulbs, it is common to find that most CFLs supplied to the Nigerian market are substandard and so easily burnout easily [13, 14]. Energy efficient lamps/bulbs are also far more expensive than incandescent bulbs, e.g. a 60W or 100W incandescent bulb cost about ₦40 while a standard CFL cost between ₦500 to ₦1500 for 40W and 80W, respectively. However, it is worth mentioning that some substandard CFLs could be purchased for as little as ₦150 and ₦200 [13].

Persistent power outages, brownout and few hours of electricity supply per day means that significant proportions of indoor night time lighting for many households is backed-up by other lighting sources such as kerosene lamps and smaller gasoline generators. Figure 2 shows that some households in all the study areas except Karu have between 2 to 4 kerosene lamps which are used for an average of 4hours for lighting at nights without public power supply.

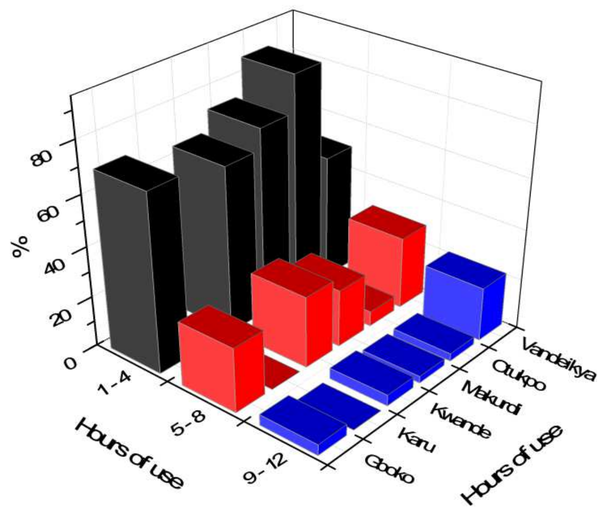

Fig. 2 Hours Kerosene lamps are used

Figure 3a shows the number of hours household in the studied area use generators when there is blackout from the public power supply. It is clear from Fig. 3a that a higher percentage of respondents used generators between 4 to 8 hours a day The most common generator used, popularly known as “I pass my neighbor” (Fig. 3b), is rated at 950 VA. Fewer lights are used with this kind of generator, due the use of inefficient incandescent lights. The generators under these loading conditions can provide electricity for four hours consuming 2 liters of gasoline fuel.

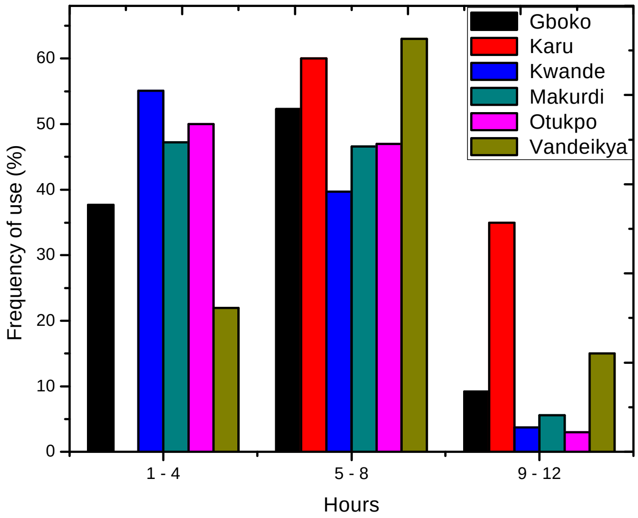

Fig. 3a Hours generators are used per day

Fig. 3b Common household generator

Energy Saving Potential

The electrical energy consumed by lighting appliances in Nigeria can be drastically reduced to meet other pressing needs if technologies such as incandescent bulbs were replaced with energy efficient lamps. The results of estimated energy savings are presented in Table 3. The result shows that about 70% of electrical energy supplied from public power supply can be saved annually if incandescent bulbs are replaced with EELs. The huge quantity of electricity that can be potentially saved could be consumed by other services (end uses), increase the hours of reliable electricity supply, or increase access to electricity such as those communities that are yet to be connected to the national grid system. Also, EELs can reduce energy bills, thereby freeing up money that can be spent elsewhere in the economy.

Table 3: Estimated energy saving potential from efficient lighting technologies in Nigeria

Area	Total Households with Electricity	Electrical Lighting Energy Consumption (GWh/yr)		Percentage Savings %
		Incandescent Bulbs	**CFL**	
Sample Areas	1,637	1.6	4.8	70.0
North Central Nigeria	1,107,087	1080	320	70.4
Nigeria	10,323,427	10100	3303	69.7

Now that the energy saving potential has been shown, the question remains: what approach can we use to drive the EELs into Nigerian households? There are basically two approaches; technological approach and behavioural approach. For the technological approach government must develop policies that will encourage the use EELs such as banning the importation and use of incandescent bulbs, increase surveillance on substandard EELs, and by substantially subsidizing the cost of EELs. Behavioural approaches include improving efficiency and energy wastage awareness through educational campaigns.

Conclusion

Efficient energy utilization through the use of efficient lighting technologies to replace incandescent lamps promises to be the short term solution to the prevailing energy crisis in Nigeria. A saving of about 70% of the electrical energy consumed by lighting appliances can be achieved by replacing incandescent bulbs with energy efficient lights (EELs). However, this can only be possible through changes in consumer behaviours toward EELs and government policies that encourage the use of these efficient technologies. The energy saved as a result of using EELs can be used for other purposes that may enhance the overall economic growth of the country.

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Consumer Electronics

Residential Consumer Electronics Energy Consumption in the United States in 2013

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Abstract

We performed a comprehensive characterization of consumer electronics (CE) energy consumption in U.S. homes in 2013, with 17 product categories evaluated in detail. Our bottom-up approach drew upon numerous data sources, including field measurement campaigns, energy consumption studies for individual product categories, ENERGY STAR measurement databases, targeted measurements by Fraunhofer, and manufacturer product specifications. To better understand CE usage, we also surveyed 1,000 demographically representative U.S. households about how they used different CE. We found that approximately 3.8 billion CE devices consumed 167 TWh in 2013, representing about 12 percent of U.S. household electricity use. This estimate is about 12 percent lower than the estimate for residential CE energy consumption for 2010. Televisions, computers, and set-top boxes collectively accounted for about 65 percent the energy consumed. Relative to 2010, the annual electricity consumption (AEC) of televisions has decreased by more than 20 percent, reflecting a decreased installed base of older CRT TVs and average TV power draw in all modes. Since 2010, the installed base of all computers, including tablets, has increased by 21 percent, with a shift away from desktop and portable computers in favor of tablets. Due to the much lower unit energy consumption of tablets relative to desktop and portable computers, we estimate that total computer AEC has decreased by 29 percent. In addition, we estimate that the installed base and AEC of monitors has decreased by 26 and 54 percent, respectively.

Introduction

Consumer electronics (CE) are the most dynamic energy end use in buildings. Relative to other end uses, CE characteristics typically change very quickly due to product innovation, short product cycles and lifetimes, evolving usage patterns, and rapid technology adoption that can strongly influence device power draw by mode. Consequently, the characteristics of the installed base of many CE have changed appreciably since the last comprehensive evaluation of residential CE energy consumption (for the year 2010 [1]). Such rapid changes in the energy consumption characteristics of CE make it essential to develop up-to-date and accurate assessments of CE energy consumption. If older data are used to analyze potential energy policy decisions, such as voluntary or mandatory regulatory energy-efficiency programs, they can lead to less effective policy decisions that may not achieve their end goals. Consequently, the Consumer Electronics Association (CEA) commissioned Fraunhofer to perform this study to provide high-quality data to inform CE policy decisions.

National Energy Consumption Calculations

Unit Energy Consumption and Annual Electricity Consumption Calculation Methodology

We used a bottom-up approach to evaluate the Annual Energy Consumption (AEC) of most CE device categories (see Figure 1). For those, we developed usage estimates or annual average time spent in each power mode (in hours). The product of the average usage and power draw (in watts) in each mode yields the annual unit electricity consumption (UEC) in each mode (in kWh/year). The sum of the UEC over all modes equals the total device UEC, and the product of the UEC and the installed base (number of units) equals the AEC. Prior studies of CE energy consumption describe this methodology in further detail [1-5].

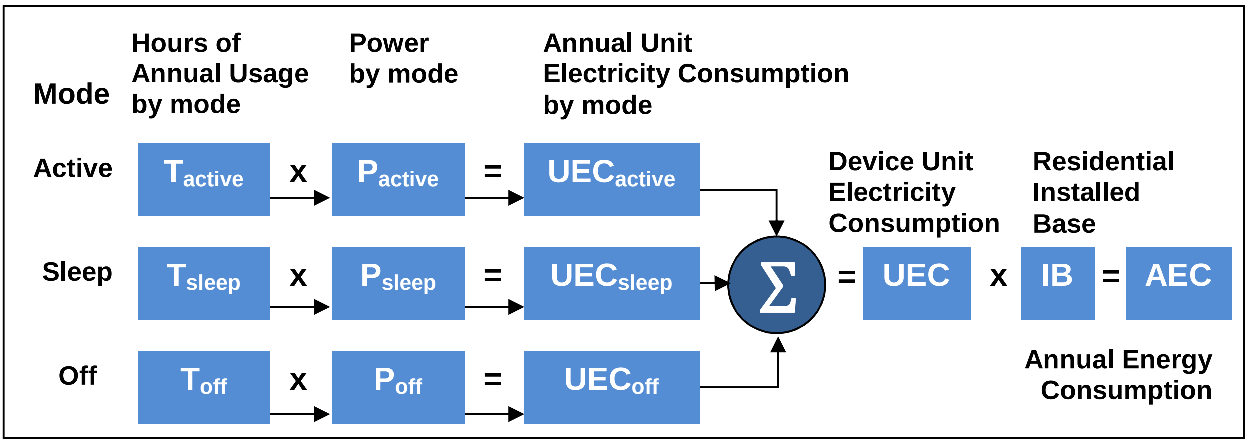

Figure 1: UEC and AEC calculation methodology [3].

We used a modified approach to calculate the UEC of mobile devices, as they are typically used while running on batteries. For smart phones and tablet computers, we calculate the UEC by estimating the energy consumed to charge their batteries according to different usage scenarios we identified through phone surveys. In addition, we also evaluated the energy consumed by their battery chargers while plugged into the wall outlets when the devices were both connected and disconnected.

Residential Installed Base

The residential installed base equals the total number of devices actively used in homes, excluding devices that are not used (e.g., those stored, unplugged in basements or closets). Most installed base estimates came from market research studies (most notably [6-7]), the CE Usage Survey (described below), and, to a lesser extent, CE sales data. To ensure that the CE Usage Survey questions about ownership did not capture devices in storage, we specifically asked about the ownership of devices that have been plugged in within the last month. Typically, the installed base estimates have the lowest uncertainty of any AEC component.

Usage by Mode

Usage by mode is the most challenging aspect of UEC to quantify. For some products, we used field monitoring data to evaluate usage patterns. Unfortunately, few field studies evaluating CE usage have been completed that included large, random samples. To gain greater insight into CE usage, we organized surveys of 1,000 demographically representative U.S. households (henceforth referred to as the CE Usage Survey; more details in [8]). The surveys asked respondents questions about CE installed in their household and how they are used. The questions ultimately posed were developed by Fraunhofer in close consultation with the CEA Market Research Team, which regularly performs surveys on a variety of topics. Subsequently, we processed the responses in category-specific models to estimate the installed base of CE and CE usage. The surveys focused on CE categories with the highest energy consumption and/or greatest usage uncertainty (see Table 1), and were fielded in late 2013 and early 2014 (see [8] for details).

Power Draw by Mode

All consumer electronics have at least two basic operating modes, e.g., on and off/standby, and most have more. For many CE, the operational power draw can vary appreciably due to changes in operation, e.g., computer processor utilization scaling. For each CE category, we identified the most relevant power modes and developed estimates for the average power draw of its installed base in each mode.

Ideally, our assessment would use measurements of CE deployed in a larger sample (of at least several hundred) of demographically representative U.S. households to generate the power draw by mode estimates. Unfortunately, the cost and time required to perform such a study was beyond the scope of this project. Instead, we relied upon several different sources to estimate power draw by mode, including:

- Field measurement campaigns
- CE energy consumption characterization studies
- ENERGY STAR measurement databases
- Targeted measurements by Fraunhofer
- Manufacturer product specification
- Measurements by CEA member companies

We were able to consult multiple sources for most CE categories, which increased our confidence in our estimates of power draw by mode. Further detail about how the power draw by mode estimates were developed for specific categories can be found in [8].

Categories Selected for Further Study

Although this study would have ideally evaluated the AEC of all CE in greater detail, time and scope constraints required that we focus our effort on the CE categories where a more refined analysis would provide the greatest value. Consequently, in conjunction with CEA, we selected 17 distinct CE product categories for more refined analysis based on a preliminary AEC assessment of a larger list, favoring categories with higher AEC and higher uncertainty. In addition, we used the preliminary AEC estimates to characterize the products not selected for more refined analysis.

Table 1 summarizes the products selected for further analysis. Since a relatively small number of CE categories account for the vast majority of all CE energy consumption, this approach does not have a major impact on the accuracy of our estimate for total residential AEC.

Table 1: CE Categories Selected for More Refined Analysis

Included in Usage Survey	Not Included in Usage Survey
Compact Audio	Internet Access Device (IAD)
Computer Speaker	Modem
Desktop Computer	Monitor
Portable Computer	Router
Smart Phone	Cable Set-top Box (STB)
Speaker Dock	Satellite STB
Tablet	Stand-alone STB*
Television	Telco STB
Video Game Console	

*Stand-alone STBs include digital media adaptors, stand-alone digital video recorders (DVRs), and over-the-air digital television adapters (OTA-DTA)

Findings

We estimate that about 3.8 billion CE devices in 119 million U.S. households [6] consumed 167 TWh of electricity in 2013. This equals about 12 percent of residential electricity consumption and 8.4 percent of residential primary energy consumption [9-11]. Figure 2 shows the breakdown of CE energy consumption by category. Three product categories, televisions, computers (including monitors and computer speakers), and set-top boxes together accounted for about 65 percent of CE electricity consumption.

Figure 3 summarizes the installed base[1] breakdown of the categories evaluated in more detail. In addition, we estimate that there are 2.1 billion “other” CE devices in U.S. homes. Although these other” devices account for a majority (55 percent) of the CE installed base, we estimate that they represent about 17 percent of total AEC.

[1] For most of the categories evaluated in more detail, the installed base estimates represent the number of devices plugged in sometime in the past month.

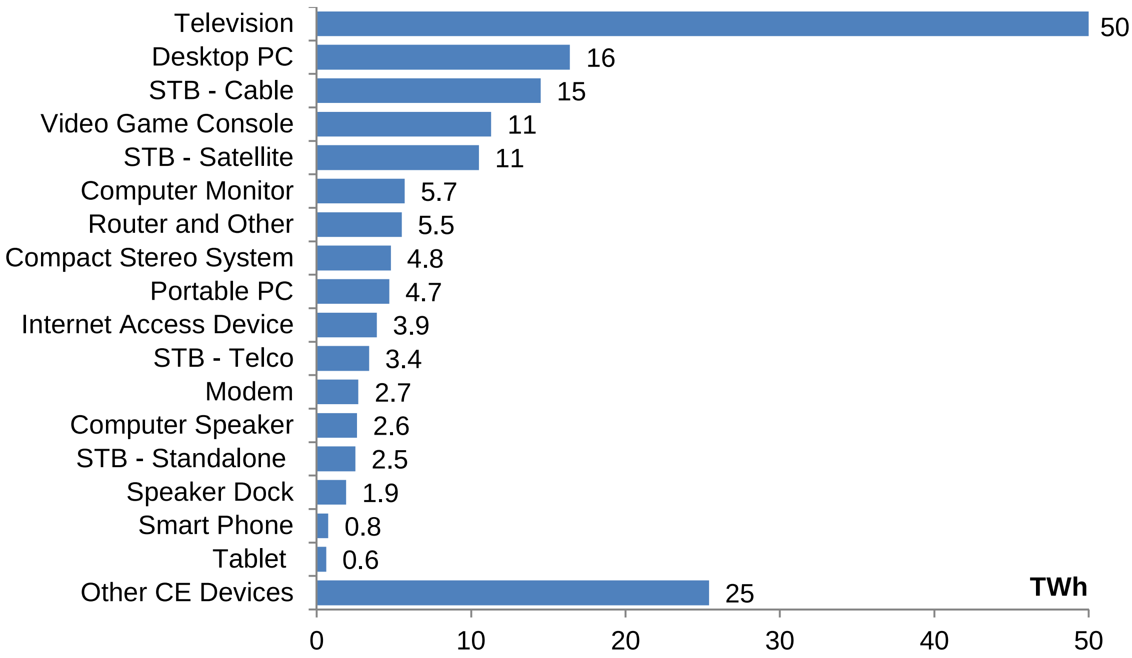

Figure 2: Annual Energy Consumption of U.S. Residential CE in 2013 by category.

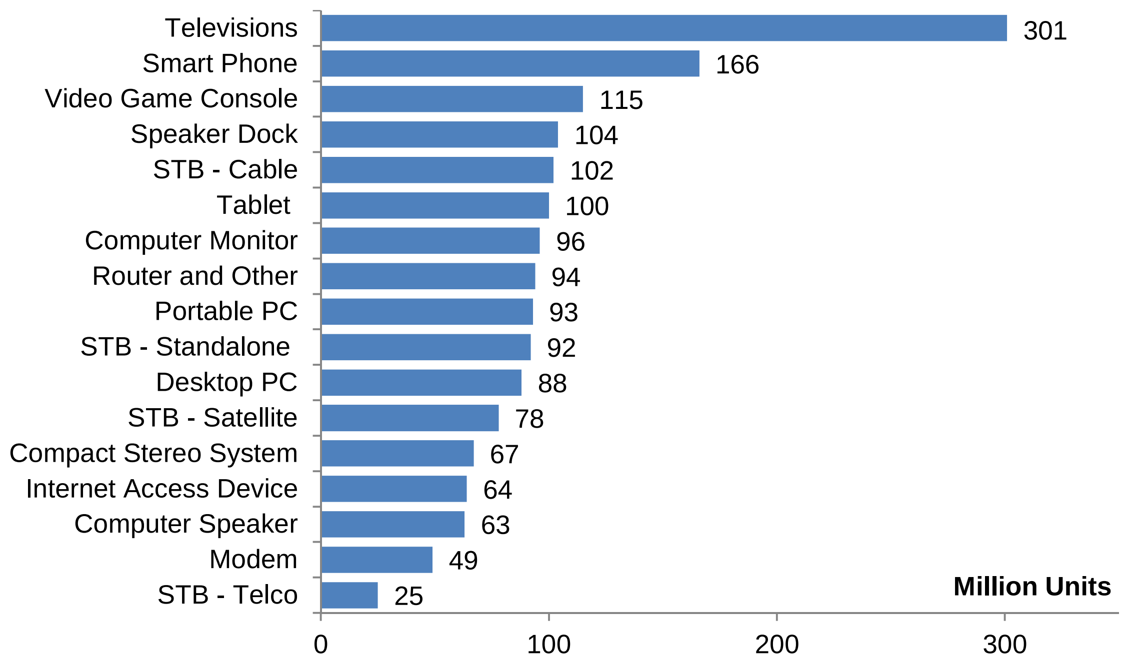

Figure 3: Installed Base of U.S. Residential CE in 2013 for categories evaluated in more detail.

Table 2 presents the average usage and power draw by mode estimates for the categories evaluated in more detail. Please note that the mode categories presented are approximate for some CE categories. In addition, we used a different methodology to calculate the UEC of smart phones and tablets. Reference [8] includes further details about the specific operating modes used for different categories. Figures 4 and 5 summarize the UEC breakdown by operational mode for the categories evaluated in further detail.

Table 2: Usage and power draw by mode for product categories investigated in more detail.

Category	Usage by Mode (hours)				Power Draw (W)			
	On or Active	Idle	Sleep	Off or Standby	On or Active	Idle	Sleep	Off or Standby
Desktop PC	1,248	1,541	2,088	3,883	70	56	3.4	1.6
Portable PC[2]	1,139	620	2,202	3,601	30	17	1.6	1.1
Computer Monitor	1,533	-	4,453	2,774	34	-	0.9	0.6
Router and Other	7,826	-	-	934	7.4	-	-	1.0
Internet Access Device	7,826	-	-	934	7.7	-	-	1.5
Modem	7,826	-	-	934	7.1	-	-	0.1
Computer Speaker	986	4,125	-	3,649	19	4.2	-	1.5
Compact Stereo System	1,241	949	-	6,570	30	12	-	4.0
Speaker Dock	1,205	2,007	-	5,548	4.8	3.0	-	1.3
Television	1,606	-	-	7,154	90	-	-	1.6
STB – Cable	5,475	-	3,285	-	16	-	14	-
STB – Satellite	3,942	-	4,818	-	14	-	12	-
STB – Telco	4,818	-	3,942	-	13	-	11	-
STB – Standalone	6,826	-	1,935	-	6.1	-	3.1	-
Video Game Console	355	885	-	7,521	58	51	-	2.6

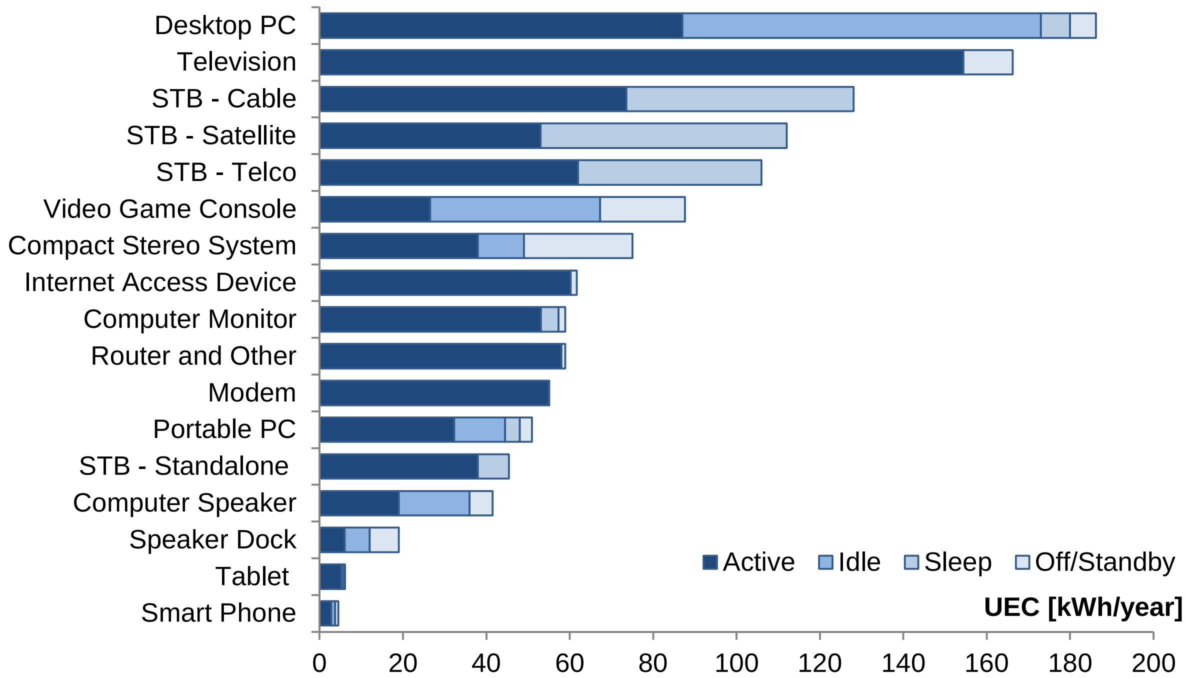

Figure 4: Unit electricity consumption for the CE categories evaluated in detail.

Our estimate for residential CE electricity consumption is 12 percent lower than that for 2010 [1]. The following subsections describe the key changes from 2010 responsible for this decrease for the three product categories that accounted for a majority of electricity consumption in both 2010 and 2013: televisions, computers, and set-top boxes.

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[2] Values have been updated from [8] for active-on and idle modes due to correction of a calculation error. Standby/off hours exclude an estimated 1,197 hours per year portable PCs are off with the external power supply unplugged.

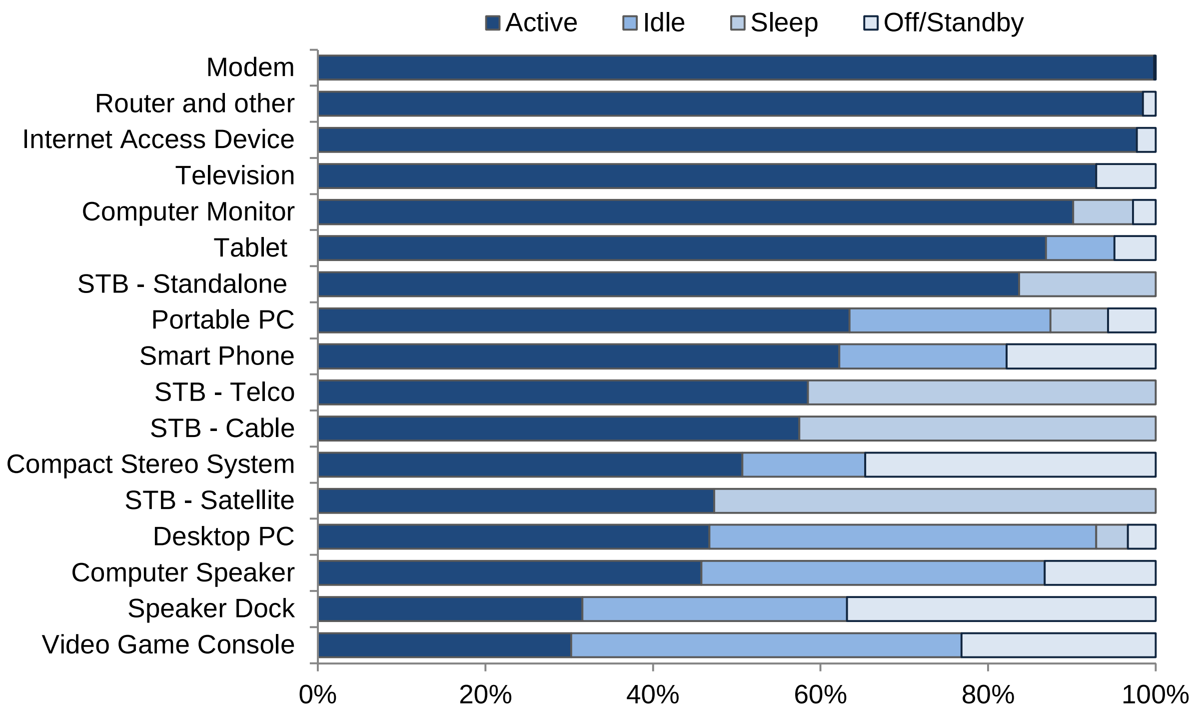

Figure 5: Breakdown of UEC by operational modes for the categories evaluated in detail.

Televisions

Since the first evaluation of CE energy consumption for 2006 [5], televisions have always accounted for the largest portion of CE energy consumption. For the first time in over a decade, the estimated number of plugged-in TVs has decreased significantly, by 52 million units (15 percent) from 2010 to 2013. This, together with a shift from CRT to LCD TVs resulted in more than a 20% decline in estimated TV AEC from 2010 to 2013. Around 90% of the 40 million TVs sold per year are flat-panel LCD displays [7], and these have overtaken CRTs as the most prevalent display technology deployed in homes. Our best understanding of this decrease of TVs plugged in within the last month is that a large portion of older, less-efficient CRT displays have been removed from service and not replaced (see Figure 6). Since our only indication of this change comes from our phone survey, its precise magnitude has some uncertainty.

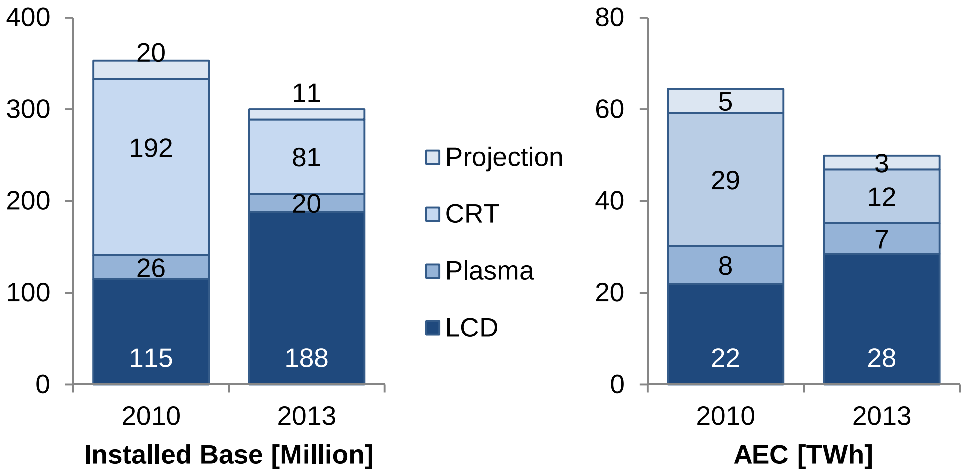

Figure 6: Television installed base and AEC by display technology.

Total active TV usage has remained fairly consistent over time, while per-TV on-time has increased somewhat from 2010. Active-mode power draw has continued to decrease (from an average of 104 W in 2010 to 90 W), even while average screen size continues to increase (34 inches in 2013, up from 29 inches in 2010 [1] and 26 inches in 2006 [5]), owing to the greater efficiency of newer displays.

Computers

We evaluated three computer types as well as smart phones in more depth. Overall, the estimated total AEC of all computers has decreased by 29 percent since 2010 (see Figure 7). A migration of the installed base to much less energy-intensive tablet computers (i.e., about nine-fold lower UEC than portable PCs) and application of more refined methods to evaluate computer usage are the main drivers for this decrease.

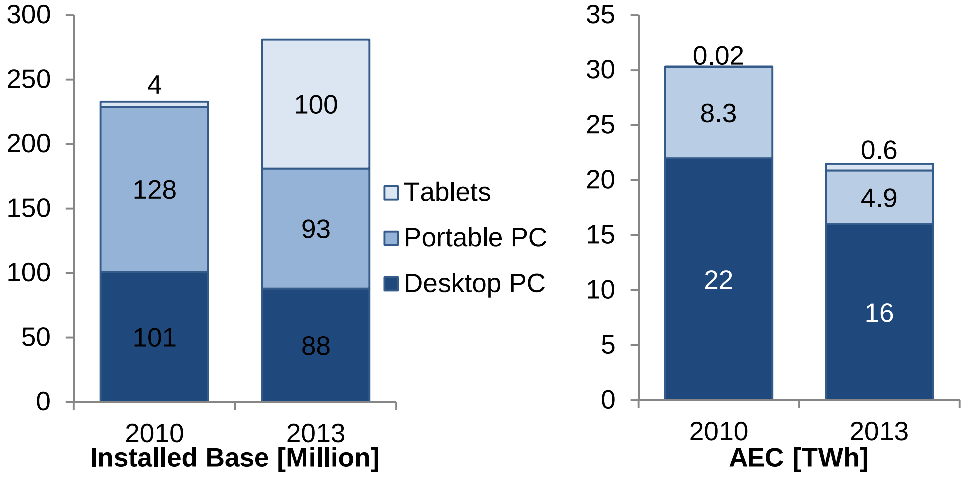

Figure 7: Computer installed base and AEC by type.

The plugged-in installed base of both desktop and portable computer decreased from 2010 to 2013 (desktop: 101 to 88 million, portable: 132 to 93 million). We believe that this is due to the 25-fold increase in the ownership of tablets, from 4 million [1] to 100 million [6]. Including tablet computers, the installed base of all computers categories in 2013 was 19 percent higher than in 2010.

We also estimated lower annual hours spent in active mode for both desktop (18%) and portable (39%) computers in 2013 than in 2010. This primarily reflects refinements in the computer usage survey and models that we think improve the accuracy of our estimates for time in operational modes for desktop PCs. Specifically, the current approach increases the precision of the survey questions posed by asking about three times of day (morning, afternoon, and evening). This provides a richer representation of usage throughout the whole day than in [1]. In addition, we think that breaking the day into more discrete time periods increases the accuracy of respondents' estimates for total computer usage.

One consequence of the decreased installed base of desktop and portable computers is a 26 percent decrease in the installed base of monitors[3]. In addition, our estimate of active-mode usage (tied to the enhanced computer usage models described above) decreased by 39 percent. That, combined with a decrease in the average power draw in all modes (due to the rise of LED backlit monitors since 2010 [12]) resulted in a 40 percent decrease in UEC. Taken all together, the estimated monitor AEC decreased by 54 percent.

Set-top Boxes (STBs)

Figure 8 depicts the breakdown of the AEC of all STBs by type in both 2010 and 2013. Since 2010, total STB AEC has increased by about 20 percent, while the installed base has increased by about 31 percent.

[3] Another factor is the increased portion (from 14 to 21 percent) of desktop computers that are all-in-one computers, i.e., devices with an integrated display.

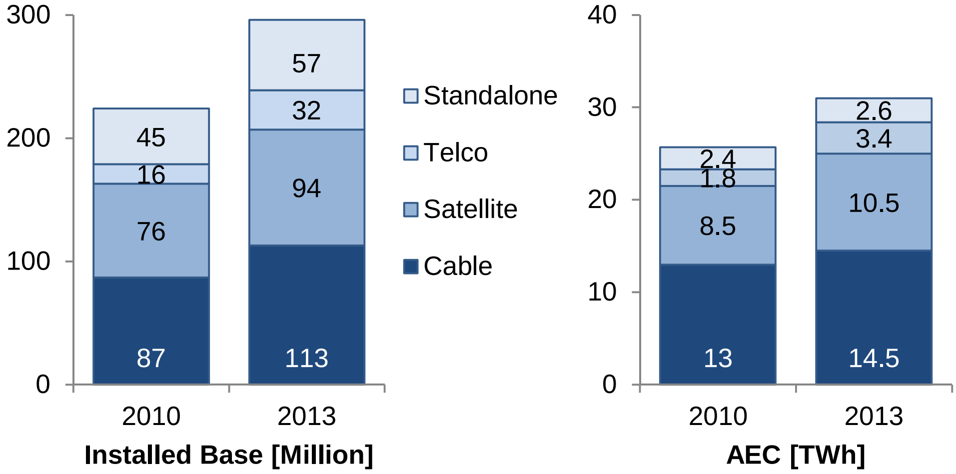

Figure 8: Set-top box installed base and AEC by type.

The installed base of cable STBs has increased by about 30 percent since 2010. This mainly reflects that the number of cable digital television adaptors has almost doubled in that period, driven by providers transitioning to digital cable service. Meanwhile, the number of satellite STBs has increased by 24 percent. For both cable and satellite STBs, the portion of high-definition units has increased. In addition, the number of telco STBs has doubled since 2010. The average power draw by mode values for pay-TV[4] STBs have not changed greatly since 2010.

Conclusions

We performed a comprehensive characterization of consumer electronics energy consumption in homes in 2013, evaluating 17 priority product categories is greater detail. For all products evaluated, we used a bottom-up methodology to evaluate AEC, developing estimates for installed base and power draw and usage by mode. The installed base estimates largely came from market research studies and the CE Usage Survey. We used power draw estimates from a wider range of sources, including field measurement campaigns, energy consumption characterization studies for individual product categories, ENERGY STAR measurement databases, targeted measurements by Fraunhofer, and manufacturer product specifications. Usage estimates were largely derived from the CE Usage Survey, a survey of 1,000 demographically representative U.S. households about how they used different CE. Notably, we refined the computer usage survey and models to improve the accuracy of our usage by mode estimates for computers. In addition, we also incorporated estimates from field monitoring studies.

We found that the approximately 3.8 billion CE devices in U.S. homes in 2013 consumed 167 TWh, representing about 12% of all U.S. household electricity use. This estimate is 12 percent lower than our 2010 estimate [1]. Together, the top three device categories, televisions, computers, and set-top boxes, accounted for about 65 percent of the energy consumed. Relative to the evaluation of CE energy consumption in 2010, the AEC of televisions has decreased by more than 20 percent, reflecting a decrease in the installed base of older CRT TVs and average TV power draw in all modes. Since 2010, the installed base of all computers, including tablets, has increased by 19 percent. Their installed base has shifted away from desktop and portable computers to tablets. Due to the much lower UEC of tablets relative to these other computer architectures, e.g., about a nine-fold lower UEC than portable computers, we estimate that total computer AEC has decreased by 29 percent. In a related trend, we estimate that the installed base and AEC of monitors have decreased by 26 and 54 percent, respectively. Finally, the estimated AEC of STBs increased by 20 percent, while the installed base of STBs grew by about 31 percent.

[4] Pay-TV services include cable, satellite, and telco.

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“How Much More Energy do Ultra High Definition and Smart TVs Use?”

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Abstract

The transition from standard definition to high definition TVs threatened to greatly increase energy use, but minimum efficiency standards, labeling, and utility incentive programs helped encourage widespread adoption of better backlighting, optical films, automatic brightness control, and other technologies to offset those increases. The transition to ultra-high definition (UHD) represents a second, equally compelling threat to energy consumption and opportunity for energy savings. Our testing of new U.S. models in retail stores and the laboratory confirms enormous variation in energy use among models of similar size, and highlights technologies and design strategies common to the best and worst products. High dynamic range (HDR) capability, always-on smart TV features observed in some models, and the steady shift to larger screen sizes represent the greatest upward pressures on TV energy use. We urge policymakers to adopt changes to test procedures and energy efficiency specifications to better anticipate and respond to this important shift in television technologies and capabilities.

Introduction

In 2013, televisions (TVs) in the United States (U.S.) consumed approximately 50 billion kWh/yr. according to a Consumer Electronics Association sponsored study [1]. This is equivalent to the annual output of 17 average (500MW) coal burning power plants. These TVs cost consumers $6 billion per year to operate and were responsible for 28 million metric tons of annual CO_2 emissions. On average there are 2.5 TVs per U.S. household.

This level of consumption is higher than it was in the era of CRT-based, standard definition televisions, primarily because of the growth in total number of TVs in use, average hours of operation per day, and average screen size. However, total TV energy use is much lower today than originally projected with digital TVs, in part because of a concerted global effort by policymakers to test television energy use in a standardized way, set minimum energy performance standards (MEPS) to eliminate the least efficient models from the market, label TVs according to their energy efficiency, and promote the best products with financial incentives in some jurisdictions. Indeed, the progress made over the last seven years improving television energy efficiency rivals the achievements recorded with refrigerators over a longer period of time.

The transition now underway to ultra high definition (UHD) threatens that record of steadily increasing energy savings for a number of reasons:

- UHD TVs have four times as many pixels as HD TVs, increasing screen opacity and typically requiring brighter, more power consumptive backlights to deliver equivalent image brightness to the user. (UHD TVs typically have a resolution of 3840x 2160, which is commonly referred to as 4K).
- Global shipments of UHD TVs are expected to rise from 12.1 million units in 2014 to 100 million by 2018 according to recent forecast by Strategy Analytics [2].
- Manufacturers and retailers are aggressively promoting larger screen sizes as a way to ensure that the higher resolution of UHD TVs is visually apparent to users.
- Smart TV capabilities associated with internet connectivity have become nearly ubiquitous in UHD TVs, increasing processing and networking power and the likelihood that they will remain connected after users have switched their televisions into a low power mode.

- 4K resolution, high dynamic range (HDR), wide color gamut, high frame rate, and enhanced audio capabilities associated with the new UHD Blu-Ray standard and associated streaming standards collectively have the effect of dramatically increasing the rate at which digital data flow into televisions. This, in turn, tends to increase the power TVs consume to process and render that information to users. The higher contrast ratios and more vividly saturated colors will improve the TV viewing experience, but increase energy use accordingly.

In order to better understand the energy impacts of some of these new features, the Natural Resources Defense Council (NRDC) retained Ecos Research to perform basic in-store testing of a cross section of 2014 and 2015 models with laboratory grade equipment and more comprehensive testing of 11 different 2015 models in the laboratory. The testing focused on models with a 55 inch screen size, as these represent a very popular, affordable price point for fully featured UHD TVs available on the US market today. We did not test smaller UHD TVs, like the 42 inch models which are very popular in the HD marketplace, as most viewers would not be able to observe the UHD resolution benefits under normal viewing conditions. Our main areas of focus were to understand the On mode power used by UHD TVs and the impact of Smart TVs and their internet connectivity on standby power. The specific research questions the study was designed to answer include:

- Do UHD TVs consume more power than similar sized full HD TVs in active mode?
- Is there a wide range in the “On mode” power levels among various UHD TV models of the same size?
- What impact does the automatic brightness control (ABC) feature have on measured “On mode” power?
- What impact does the resolution or source of the incoming content have on “On mode” power: is there any difference when receiving HD vs UHD content? Or when receiving UHD content via streaming vs from a disc played on an upscaling Blu-ray player?
- What are the Standby power and boot times for Smart TVs with Quick Start feature enabled and disabled?
- What issues, if any, were identified regarding the official test methods used to perform the measurements?

Testing and Sampling Plan

Our research had three components: a) review and analyze public databases of TV energy use managed by the California Energy Commission (CEC), ENERGY STAR program, and the US Department of Energy (DOE); b) perform in-store testing of selected 2014/2015 UHD models; and c) perform laboratory testing of selected 2015 UHD models. Our in-store testing allowed us to gather data without having to purchase the TVs, many of which were newly introduced at prices of $3000 or more. As we were unable to control the ambient lighting levels in the store, the in-store testing was done without the TVs’ automatic brightness control (ABC) enabled. The results of our in store testing informed the models we would purchase and test in the laboratory, which included testing TVs with ABC enabled. The focus of our testing was on UHD TVs that ranged between 50 to 65 inches in diameter, with attempts to purchase 55 inch models whenever available to allow for comparisons among similar sized TVs. Due to budget constraints, we performed testing on a total of 21 TVs, roughly half in-store and half in the laboratory.

In addition to this testing, we also analyzed the above databases to understand how the manufacturer reported energy use of the top four brands (Samsung, LG, Vizio, and Sony) of TVs in the 50 to 60 inch range varied between HD and UHD models, and between model years 2014 and 2015.

A listing of each of the 11 models to be tested in the laboratory along with details on the TVs’ features and the results of our On mode power measurements is presented in Figure 1. In deciding which models to test, we tried to select a broad cross section of models by choosing multiple brands, and a range of display technologies and operating systems to understand which variables have the greatest impact on On and Standby mode power consumption. Many new models shown at the Consumer

Electronics Show (CES) in January 2015 were released to the market later than expected, so testing of the low-priced Hisense and Spectre models and the newest Panasonic model with “always on” voice recognition is still in-process and their results are not yet reflected in our findings. This article reflects the testing performed to date and will be updated once the testing of the remaining three models is complete.

All laboratory testing of “on mode” power use was performed in accordance with the DOE test method [3] which utilizes a set of dynamic test clips from the IEC and static test patterns on a Blu-Ray disc that has been incorporated into testing standards around the world. Use of standardized content is important, as on mode power can vary significantly depending on the colors and average picture level (APL) of the images being displayed. In addition to following the setup instructions defined by DOE, we then performed additional testing with certain features enabled or disabled to understand what impact that might have. For example, if a Smart TV shipped with Quick Start disabled, we tested it this way for official testing and reporting purposes and then also tested it with that feature enabled to gather data on what impact it would have on start time and Standby power use. Similarly if a TV was shipped with ABC on, we tested the TV a second time with ABC disabled.

For both lab and retail testing, a stable AC waveform was provided to the TV using a Chroma 61602 reference power source. Real time power analysis and data logging was performed using a Yokogawa WT-310 analyzer interfaced to a custom LabVIEW software interface. Test equipment and tolerances were configured per the DOE/IEC standards and a sample rate of 250ms was used for all measurements. During ABC testing, room illuminance was measured using a Konica T-10A meter. All test equipment held valid calibration certificates at the time of test. Because the IEC test disc and all content available on Blu-Ray disc still has a maximum resolution of 1080p, we utilized an OPPO Blu-Ray player to upscale that content to 4K or streamed native 4K content from the internet in other cases to better understand the incremental energy consumption associated with that capability.

Within the test methods, there are multiple low power modes corresponding to varying levels of processor activity and power consumption. Standby-passive is the lowest level of standby whereby the TV is not able to send or receive data, and standby-active low is the state where an internet connected TV is capable of receiving or sending data. When a TV is in standby and actively receiving or sending data, such as updating an App or receiving a firmware update, it is in standby-active high mode. Our testing did not include standby active high mode, given its typically brief duration within an overall annual duty cycle of operation. (Note – during testing of the Sony 2015 model, it is unclear whether the TV was in standby-active low or standby-active high mode.)

Testing Results and Observations

All in store and laboratory testing was performed between April and June 2015. A description of each of the 11 models purchased for laboratory testing is provided in Figure 1 along with the results of our On mode power testing. To be determined (TBD) is shown in the entries for the three models where testing has not yet been completed due to their delayed availability on the market.

MFG	Hisense	LG	LG	Panasonic	Samsung	Samsung	Sceptre	Sharp	Sony	Vizio	Vizio
Model	50H7GB	55EG9600	55UF7600	TC-55CX850U	UN55JS9000	UN55JU7100	U508CV-UMK	LC55UB30U	XBR55X850C	M55-C2	P552ui-B2
Year	2015	2015	2015	2015	2015	2015	2015	2015	2015	2015	2014
Screen Size	49.5	54.6	54.6	54.6	54.6	54.6	48.5	54.6	54.6	55	54.64
Price (Amazon)	$598	$5,499	$1,399	$2,999	$2,497	$1,597	$520	$999	$1,599	$999	$999
Backlight	TBD	N/A	LED Edge Lit	TBD	LED Edge Lit	LED Edge Lit	TBD	LED Edge Lit	LED Edge Lit	LED Full Array	LED Full Array
Panel Technology	TBD	OLED	IPS	TBD	Quantum Dot	-------	TBD	-------	Quantum Dot	-------	IPS
Processor	TBD	Quad-core	Quad-core	TBD	Octa-core	Quad-core	TBD	Quad-core	-------	Dual-core CPU	Dual-core CPU
OS	TBD	webOS	webOS	TBD	Tizen	Tizen	TBD	SmartCentral	Android TV	Proprietary	Proprietary
ABC Sensor	TBD	Yes	Yes	TBD	Yes	Yes	TBD	No	Yes	Yes	Yes
Quickstart Option	TBD	No	No	TBD	Yes	Yes	TBD	Yes	No	No	No
On Mode Power (ABC On) Measured Value (watts)	TBD	108.7	48.3	TBD	77.8	60.1	TBD	No ABC Feature	91.6	67.7	107.4
On Mode Power (ABC Off) Measured Value (watts)	TBD	136.3	88.5	TBD	125.0	99.9	TBD	97.7	107.6	130.3	166.3

Figure 1: Specifications on the Models Purchased for This Study and Their Measured On Mode Power Levels

Spread in Power Use of UHD TVs Tested and Comparison to ENERGY STAR Specifications

In addition to performing testing of the models listed in Figure 1, we analyzed the manufacturer reported On mode power from the aforementioned public databases of TVs in the 50 to 60 inch screen size category for the top four brands sold in the US – Samsung, LG, Vizio, and Sony. We plotted the On mode power data from the databases and our measured values alongside the maximum allowable power curves from the U.S. Environmental Protection Agency's (EPA) ENERGY STAR labeling program. EPA's goal is to have its specifications represent approximately the top 25% of the market in terms of their energy efficiency when the new levels go into effect. ENERGY STAR Version 6 went into effect in June 2013 and the latest Version 7 goes into effect on October 30, 2015. In Version 7, EPA created separate requirements for HD and UHD models and provided a roughly 50% additional On mode power allowance or "adder" for UHD models.

Some observations from Figure 2 include:

a) There is a wide spread in the On mode power use of UHD models of equivalent screen size, sometimes by more than a factor of 2.

b) There are already many UHD models that are well below the UHD qualifying level for ENERGY STAR Version 7, several months before its effective date.

c) There are already a few UHD models on the market that meet or just exceed the ENERGY STAR Version 7 level for non-UHD models.

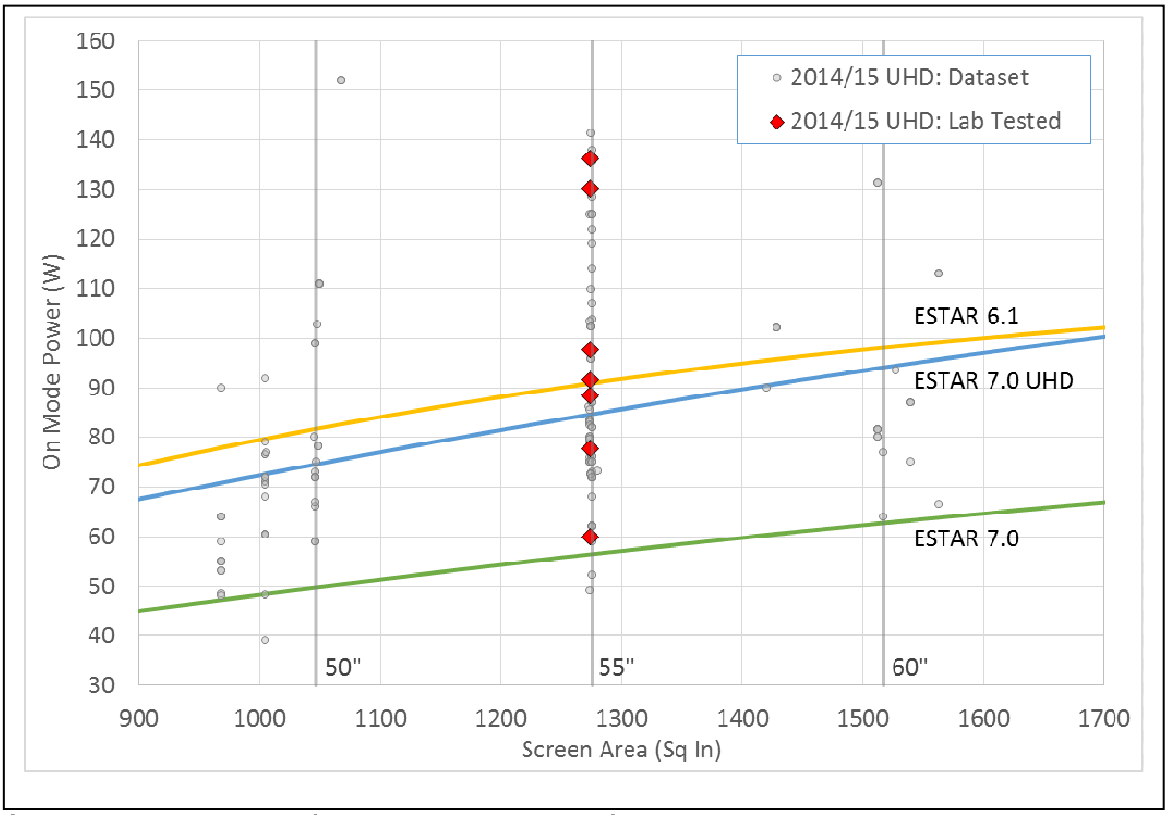

Figure 2: UHD TV On Mode Power Use Compared to ENERGY STAR Curves

FigureFigure 3 shows how the annual energy consumption (AEC) levels in kWh/yr vary for the 55 inch model TVs that we tested in the laboratory. AEC was calculated using the DOE specified daily duty cycle of 5 hours On mode and 19 hours Standby mode. The AEC levels ranged from a low of 110 kWh/yr to a high of just over 300 kWh/yr. At a national average electricity rate of 12 cents per kWh, this incremental power use translates to an extra $228 in utility bills over the ten year life of a new 55 inch TV.

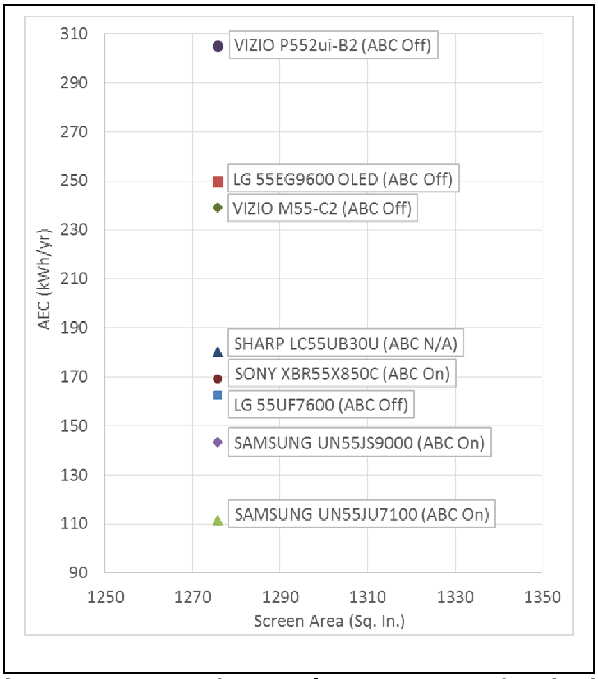

Figure 3: Range of Annual Energy Use of 55 inch TVs Tested in the Laboratory

Figure 4 provides a detailed look at the reported On mode power levels of UHD models in the public databases. The data set included 151 UHD models in 2014 and 189 UHD models in 2015. Above 60 inches, TV power use of the least efficient models rises dramatically. Some of these more power consumptive models can easily use as much energy per year as a typical refrigerator sold in the US. It is also evident that some of the most power consumptive models are so far away from qualifying for ENERGY STAR specifications that their manufacturers may not bother making small refinements in their design to improve energy efficiency. Adoption of MEPS by jurisdictions around the world could be an effective means to remove the worst models from the market.

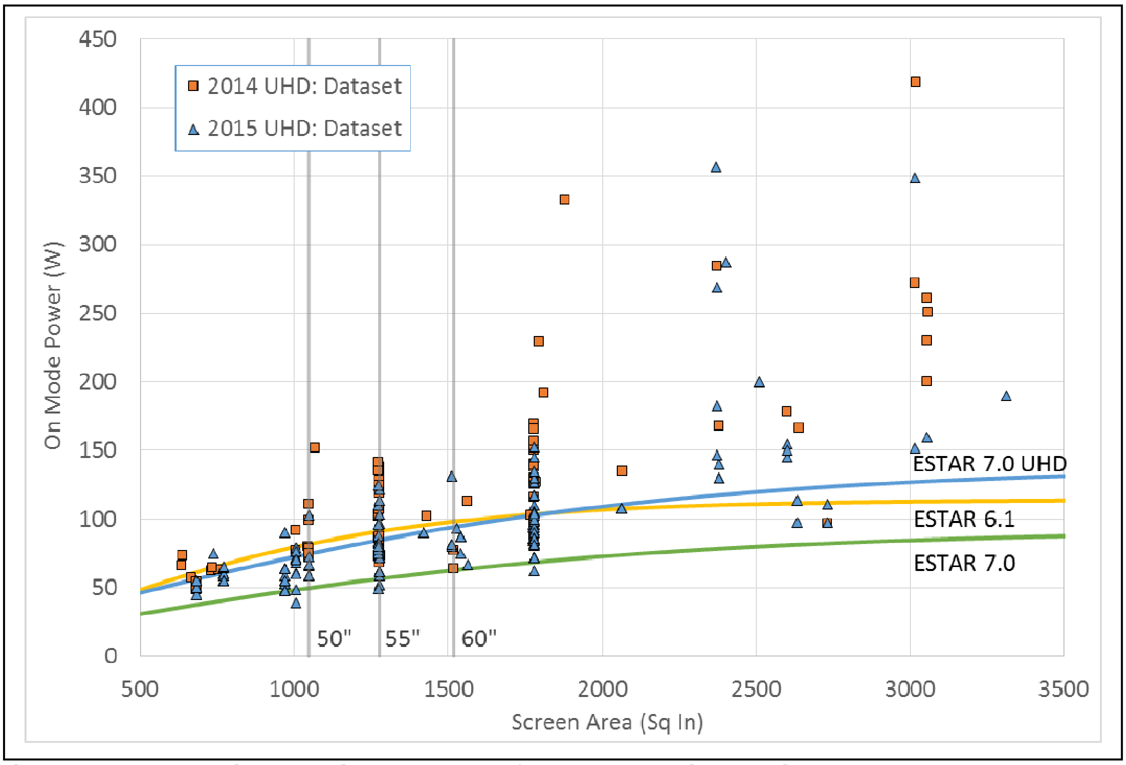

Figure 4: Reported On Mode Power Use for TVs 50 Inches and Greater

Measured Impact of Automatic Brightness Control on On Mode Power

TVs with the ABC feature contain a sensor that automatically measures the level of light entering the front of the TV and adjusts the picture brightness accordingly. The concept behind this feature is that TVs watched in a darker room do not need as bright a picture and that automatically reducing the brightness of the TV's backlight brings down the TV's On mode power use. Per the DOE test method, TVs that are shipped with ABC enabled and do not offer the user a choice to turn off this feature during the initial set up are tested with ABC on. If the TV is shipped with ABC disabled or provides the user a choice to disable it during the initial set up, then the TV is tested with ABC off. For testing done with ABC on, power measurements are made at four room illuminance levels – 3, 12, 35, and 100 lux – and the reported On mode power is the average of these four values.

*In our laboratory testing of 55 inch models we found that the UHD TVs used an average of 57% more power with ABC off than with ABC on***.** The range was from 17% to 93%. For each model tested, the On mode power value that would be reported per the DOE test method is the bar that contains the white text in Figure 5.The difference in On mode power levels between ABC on and off was the biggest for the Vizio and LG models. The Vizio model defaults to ABC off and LG users are presented a choice in the forced menu during initial TV setup. The Sharp model was the only TV we tested that did not have an ABC feature.

A closer look at the values in Figure 5 for the Vizo and LG models shows that a single change in how companies design their set up screens and implement ABC can dramatically reduce a model's reported On mode power use and in some cases result in their qualification for ENERGY STAR. In addition manufacturers would be able to report a much more competitive energy use value on the yellow Energy Guide label that compares model energy use and annual operating cost to other similarly sized models sold in the U.S. market.

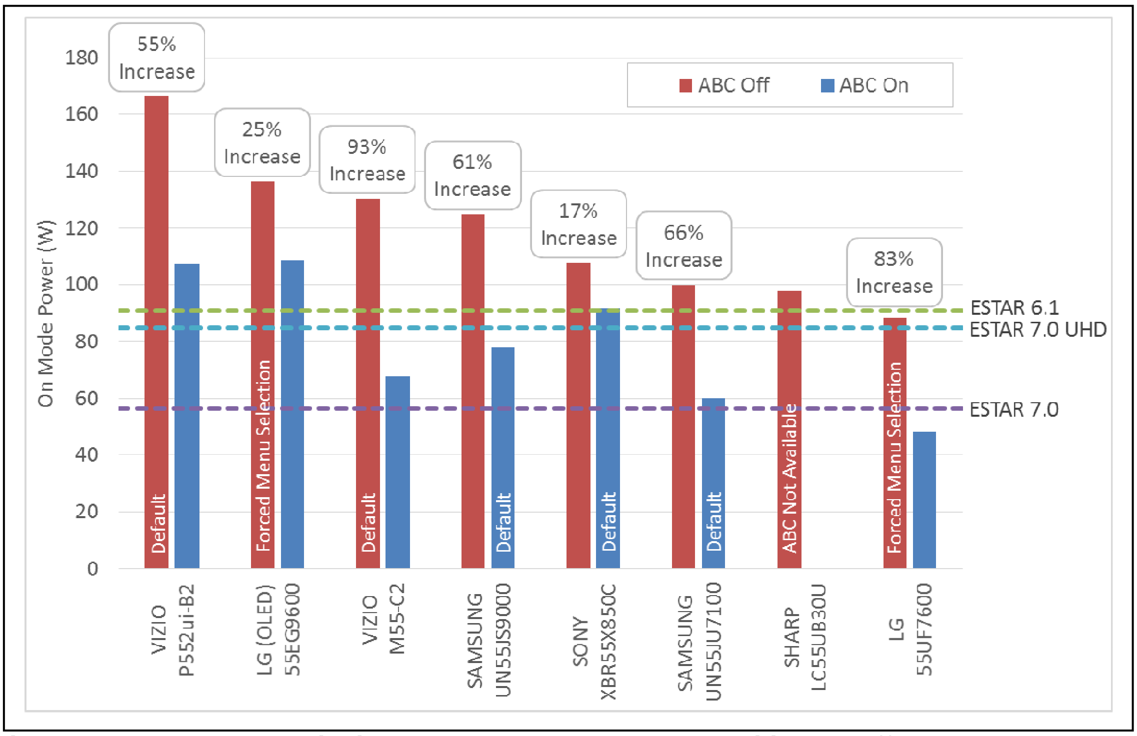

Figure 5: On average, 55 inch UHDs use 57% more power with ABC off

It also noteworthy that the European Union's eco-design requirements treat ABC very differently as TVs in Europe are tested with ABC turned off and limits the "credit" a TV with the ABC feature can receive to just 5%. Below is the excerpted text from the EU regulations No 1062/201 [4].

For the purposes of calculating the Energy Efficiency Index and the annual on-mode energy consumption… the on-mode power consumption as established according to the procedure set out in Annex VII is reduced by 5 % if the following conditions are fulfilled when the television is placed on the market:

a) *The luminance of the television in the home-mode or the on-mode condition as set by the supplier, is automatically reduced between an ambient light intensity of at least 20 lux and 0 lux;*

b) *The automatic brightness control is activated in the home-mode condition or the on-mode condition of the television as set by the supplier.*

As such, care should be used when comparing reported On mode power levels reported in the US and the EU. It would also be interesting to investigate whether models shipped to Europe are less likely to come with ABC feature than those in the US given the much smaller impact this feature has on the reported On mode power level.

Impact of Receiving HD or UHD Content or Input Method on Measured On Mode Power

Although there has historically been minimal availability of native 4K content, its availability is increasing as Netflix, Amazon, YouTube, and other streaming services have begun supporting it and UHD Blu-Ray standards have been finalized for implementation later this year. Today's UHD TVs upscale or up-convert incoming HD content to their screens' native 4K resolution. It is not known how UHD On mode power use would change if the TV receives native UHD signals. One might assume the measured power values would be lower as the TV does not have to perform the processing to upscale the signal. Alternately, some TVs might boost the screen brightness levels when displaying native UHD content. In an attempt to assess this issue, our testing included two On mode power tests of the IEC test clip on an OPPO Blu-ray player. For the first test, the signal received from the Blu-Ray player had a resolution of 1080i, which was then up-converted by the TV to 4K, and for the second test the signal was up-converted in the player to 4K and sent to the TV. To ensure consistent testing results, all of the testing was done with ABC disabled. This testing was done in the store and the models shown include both 2014 and 2015 models, and most are different than those we purchased for laboratory testing.

Figure 6 shows that on average the tested UHD TVs used 10% *more* power when displaying native 4K content compared to HD. One particular outlier is the Samsung 65JS9500 UHD TV we tested that showed a 46.8% increased On mode power level when displaying 4K content. Given the size of this difference, and the fact that the JS9500 represents the most fully featured and favorably reviewed new model of its size, it would be worth exploring this model's performance further.

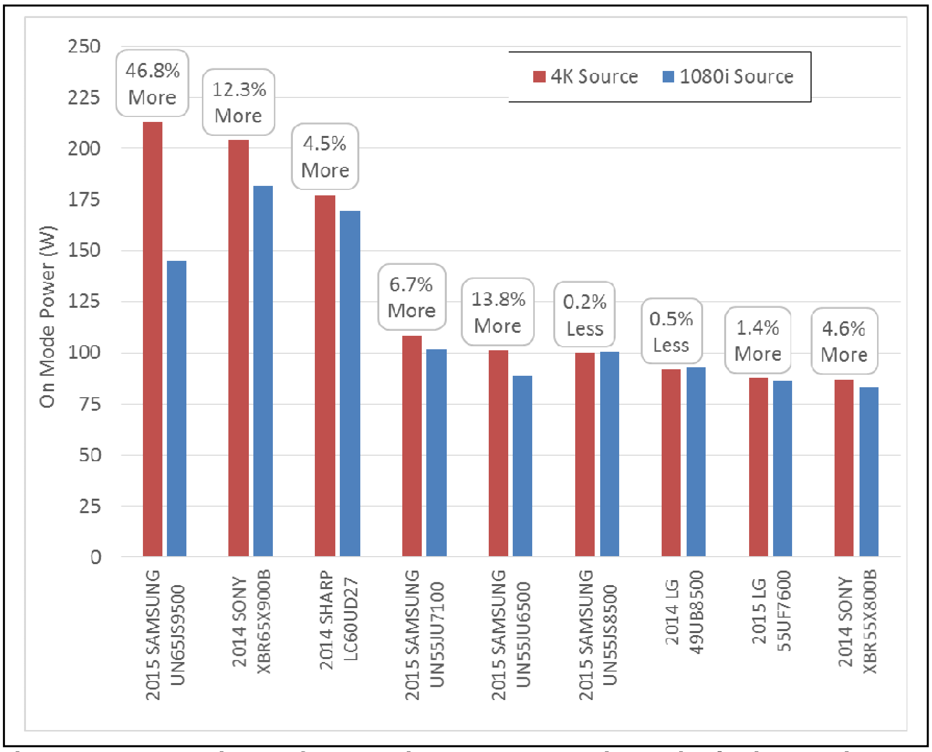

Figure 6: Comparison of On Mode Power Use When Displaying Native 4K vs HD Content

Separately we examined the impact that the signal source had by comparing the On mode power used when streaming a movie vs when played on disc. To perform this comparison we used a 10.5 minute clip from the movie *Crouching Tiger Hidden Dragon* and tested the power levels when a 4K signal was received via streaming over Netflix and by playing the same clip from a 1080p disc that was up-scaled by the Blu-ray player to 4K and then fed to the TV. Figure 7 shows the relatively small impact that internet streaming had on most of the TVs that were tested. Again, all of these tests were run with ABC off.

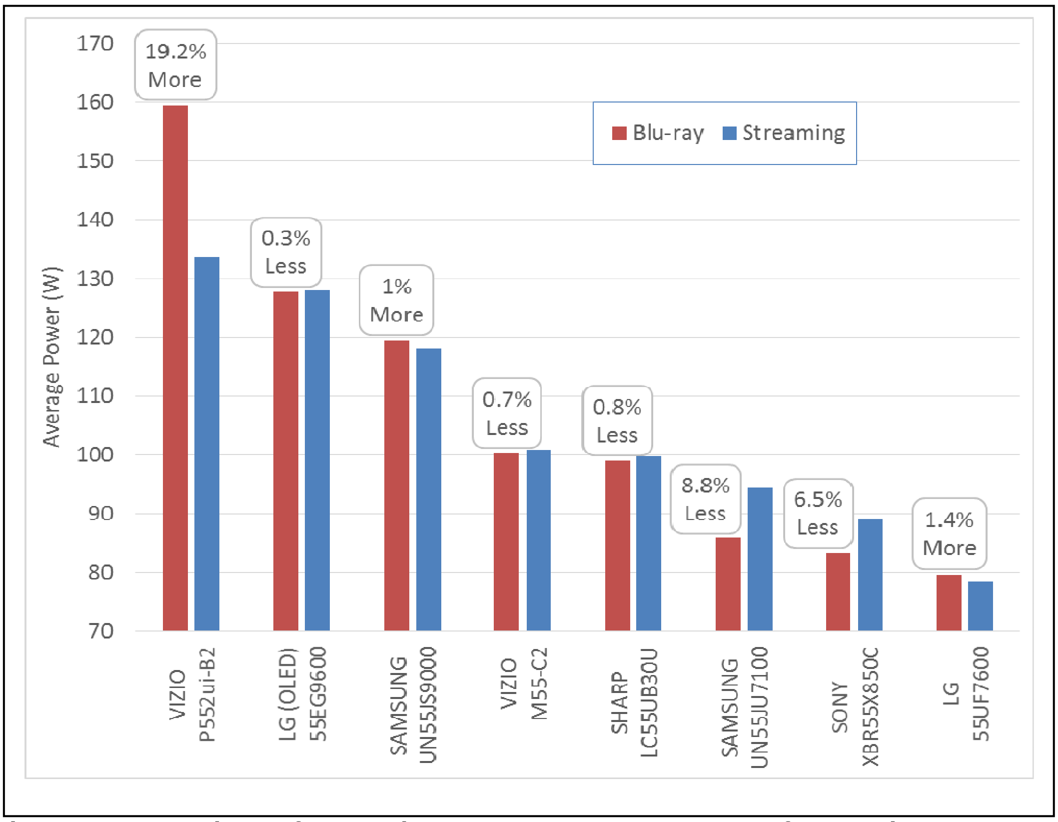

Figure 7: Comparison of On Mode Power Use - 4K TV Content from a Disc vs Streaming

Standby Power Levels of Internet Connected TVs ("Smart TVs")

The majority of TVs sold today can access the internet wirelessly or via Ethernet connection without the use of a Roku box, Google Chromecast, Apple TV or similar external device. TVs with this functionality are generically referred to as Smart TVs. Their internet connectivity allows consumers to stream movies via applications such as Netflix on their TVs and to search the internet for YouTube videos and other content. Some of the first Smart TVs had boot times, the time needed for a TV to restart from off and re-establish a live internet connection, of 15 to 30+ seconds. As a result, some manufacturers added a "Quick Start" feature which reduced the boot time, but caused a big jump in a TV's standby power. In the first versions of Google TV that were incorporated into Sony's initial Smart TVs, the standby power with Quick Start selected was 24 W. At 19 hours per day, the Standby energy use alone would be 166 kWh/yr., which could result in a doubling of the TV's *total* annual energy use.

In their 2015 models, manufacturers have increased the number of applications available for use on Smart TVs, updated the underlying software and hardware, and are heavily promoting these capabilities. To better understand how boot time and standby power use levels vary with and without Quick Start selected, we tested a range of 2014 and 2015 models. The results of this testing are shown in Figure 8.

Boot times of less than 10 seconds and standby power use of <0.3 W were observed for the Samsung and LG models. The Vizio models tested had a very low standby power level as well, 0.2 W, but had slightly longer boot times of 15 seconds. At the other extreme were the Sony and Sharp models which had much higher standby power levels when Quick Start was selected. The 2014 and 2015 Sharp models tested with Quick Start on had standby power levels and boot times of: 25.2 W and 8.9 seconds, and 9.3 W and 5.7 seconds, respectively. Without Quick Start selected, these TVs had boot times of 19.5 and 17.9 seconds, which are longer than what some consumers may find acceptable. As such, many consumers are likely to go into the menu at a later time and select the Quick Start setting which could result in 62 extra kWh/yr. of standby energy for the 2015 Sharp model. Per the test method, this significant additional annual energy use would not be captured in this case with the Quick Start feature disabled.

Year	UHD Model	OS	Quick start Off		Quick start On	
			Standby Power (W)	Boot Time (s)	Standby Power (W)	Boot Time (s)
2014	LG 49UB8500	webOS	0.10	9.0	N/A	N/A
2015	LG 55EG9600	webOS	0.13	9.7	N/A	N/A
2015	LG 55UF7600	webOS	0.17	6.7	N/A	N/A
2015	SAMSUNG UN55JS8500	Tizen	0.15	6.4	0.24	5.4
2015	SAMSUNG UN55JS9000	Tizen	0.07	6.2	0.20	4.5
2015	SAMSUNG UN55JU6500	Tizen	0.11	6.9	0.22	5.1
2015	SAMSUNG UN55JU7100	Tizen	0.18	6.6	0.28	5.0
2015	SAMSUNG UN65JS9500	Tizen	0.07	6.1	0.20	4.7
2014	SHARP LC60UD27	Proprietary	0.16	19.5	25.21	8.9
2015	SHARP LC55UB30U	Proprietary	0.25	17.9	9.03	5.7
2014	SONY XBR55X800B	Proprietary	0.09	12.5	34.42(**)	5.6
2014	SONY XBR65X900B	Proprietary	0.02	11.0	37.54(**)	4.0
2015	SONY XBR55X850C	Android TV	0.29/22.1(*)	8.2	N/A	N/A
2015	VIZIO M55-C2	Proprietary	0.20	15.3	N/A	N/A
2014	VIZIO P552ui-B2	Proprietary	0.20	15.7	N/A	N/A

64% less QS standby power than 2014 model

Sony eliminated QS in 2015

(*) Fluctuates between Standby passive (0.29W) and active-low (22.1W)
(**) Programmable quick start up to 6 hours per day or auto settings

Figure 8: Standby Power Levels and Boot Times for Smart TVs With and Without Quick Start Selected

When Quick Start was selected for the 2014 Sony models, the TVs drew a whopping 34.4 and 37.5 W in Standby power. However, the TVs had some additional software that would limit this high standby power to 6 hours per day, or allow the TV to learn the user's viewing times and reduce the hours which Quick Start was on and drawing these high power levels, accordingly.

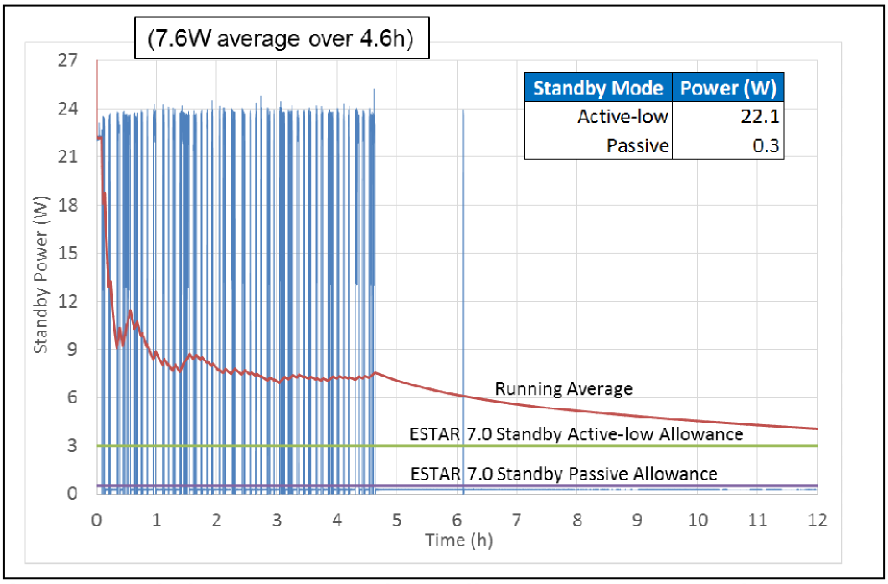

Figure 9: Variation of Measured Standby Power Use Over Time of Sony Model

The 2015 Sony Model 850 C had a measured boot time of 8.2 seconds, which is probably low enough for most users, and did not have a Quick Start option. As the power used in standby was cycling and did not stabilize, we left the power meter engaged for an extended period to record the unit's standby power use. As seen in Figure 9, the standby power cycled between 0.29W and 22.1W for a period of

4 ½ hours, at which point it then stabilized at 0.29W. The average power draw during that cycling period was 7.6 W, which translates to 12.8 kWh/yr. per cycle. This occurred each time the TV was turned on and off, meaning its contribution to annual energy use could be even higher if users watch TVs in multiple, short intervals spread throughout the day. For some users, the standby energy use would be three times this amount or 38.4 kWh/yr. if they have a usage pattern whereby they turn on the TV before work, a child watches TV or plays a video game during the early afternoon, and the parents watch TV in the evening.

Conclusions and Recommendations

The key findings from our research are:

- On mode power for the 55 inch diameter UHD TVs we measured varied widely, sometimes by more than double. Some models were very efficient and use little to no incremental power than similar sized HD TVs, while others use a lot more power.

- Above 60 inches, On mode power use of the least efficient models increased dramatically. This could result in big increases in national energy use should these large TVs gain in popularity as their costs continue to fall. 70" UHD models are now available in the US market for just under $2,000, and 80" UHD models have reached price points of $4,000 to $5,000, where they were previously unavailable at all or only sold for $20,000 or more.

- Automatic brightness control (ABC), when enabled, can dramatically reduce a TV's annual energy use. For the 55 inch models we tested, we found UHD TVs used 57% more power with ABC off compared to ABC on. Testing of more models, including those of different sizes is needed to better quantify the impact enabling ABC has on On mode power levels.

- Some but not all of the manufacturers have successfully achieved boot times of <10 seconds and standby power levels of 0.3 Watts or lower for their Smart TVs. Others had extremely high Standby power levels, the worst being a 2014 model that consumed 25 Watts continuously when Quick Start was selected. That translates to an incremental annual energy use of 174 kWh/yr. One manufacturer's TV cycled continuously between 0.3 and 22 Watts when in standby for a period of 4.6 hours after the TV was turned off, which translated to an average standby level of 7.6 Watts during that period.

- UHD TVs drew on average 10% more On mode power when receiving native 4K content instead of 1080p content during testing. There was little difference in On mode for TVs that received 4K content via streaming vs from an upscaling Blu-ray player.

Based on our learnings from this research we recommend:

1. Interested parties should obtain access to model-specific market share data and calculate the difference in energy use between HD and UHD models of similar size, and how UHD energy is changing from year to year. This data can also be used to estimate the impacts of high adoption of UHD TVs in terms of their energy use, electricity bills and CO2 emissions from power plants.

2. Policy makers should also carefully track the market share of larger TVs given its potential impact on national TV energy use.

3. Manufacturers whose models have an ABC sensor should ship these models with this feature enabled by default and without requiring its selection in the forced menu. This one easy change can dramatically reduce the amount of energy consumed by these models

4. EPA should carefully review UHD On mode power levels of the latest 2015 models and reduce the size of the UHD adder in its update to ENERGY STAR Version 7 accordingly.

5. California and other jurisdictions should adopt MEPS that extend coverage to all sizes of televisions and that reflect the emerging reality that new UHD features *can* increase TV energy consumption, but do not need to increase it by nearly the extent observed in the least energy efficient models.

6. Changes to the test method that will increase its reproducibility and accuracy include:

   a) Clarify how to measure average Standby power for Smart TV models that seem to fluctuate between standby-active low and standby-passive modes. Rather than waiting for the value to stabilize before measuring it, there may be merit to measuring it from the moment the TV is first switched off until it has stabilized to a nearly constant value for at least one hour and then reporting the weighted average power value for that entire period.

   b) Consider requiring models whose reboot times exceed 10 seconds to be tested with Quick Start selected since that is how many consumers may ultimately operate it.

   c) Re-master the IEC test clip to provide native 4K content with HDR encoding by the end of 2015 to enable more accurate measurement of TVs with those capabilities in the future. Also use representative real world content that does not contain blinking between discrete scenes which occurs in the current IEC test clip and could lead to gaming by a smart TV manufacturer whereby the TV detects that it is being subjected to the energy test and alters its performance in order to deliver a lower, more favorable power use value.

7. Conduct preliminary testing of HDR-capable TVs with High Dynamic Range (HDR) content to better quantify the resulting energy consumption impacts.

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How Low Can You Go? Forecast of Game Console Energy Consumption Based on Industry Trends

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Abstract

Each new generation of video game consoles brings with it previously unseen graphical realism and dazzling interactive features. The increased processing power of a latest-generation console also requires greater energy consumption compared to the most recent models of preceding generations. For example, the latest 8th-generation Microsoft Xbox One and Sony PlayStation 4 consoles provide full high definition (1080p) video output, video and sound input, and Internet connectivity, all enabled by an accelerated processing unit (APU) with 5 billion transistors, compared to 372 million transistors for the previous (7th)-generation consoles. This all comes at a cost: one report has calculated a cumulative energy consumption in excess of 10 TWh/year in the United States alone. How will this new load evolve over time?

Previous generations of high performance game consoles have exhibited decreasing energy consumption, as manufacturers have iteratively improved the components within each generation without changing the fundamental design. The likely primary driver of these intra-generational decreases has been “functional scaling”, a semiconductor industry trend that has taken the place of geometric or Dennard scaling as a means of increasing processor performance and continuing Moore’s Law. This trend is expected to continue, and together with power management, provides two paths for reducing energy consumption of current-generation game consoles over the next five years.

Projections based on these historical trends and semiconductor-industry roadmaps show that Gameplay Mode power draw will decrease by almost a third by 2017 and almost a half by 2020, compared to the 2013 launch models. This can be expected to decrease the annual energy consumption to 58 kWh/yr for Xbox One and 68 kWh/yr for PlayStation 4 by 2020. We also validate the forecast model against historical trends showing 14% average error for Xbox 360 and 15% for PlayStation 3. Finally, we present a high-improvement scenario based on efficient designs of other information and communications technology (ICT) products that show a potential pathway to approximately 85% energy savings by 2020.

Introduction and Background

This paper forecasts the power draw and energy consumption of current (8th)-generation high-performance game consoles[1] based on measurements conducted in 2013 [1] and 2014 [2], semiconductor industry roadmaps and forthcoming European Union (EU) connected standby regulations. We also validate the forecast model by backcasting and comparing the results to historical power draw of previous (7th)-generation game consoles[2]. Finally, although we anticipate significant reductions in power draw and energy consumption within the current generation of game consoles, the paper discusses potential measures for reducing energy consumption even further, while also locking in some of the savings into a potential, future 9th generation of game consoles, which could re-use some of these energy saving features even when the processor and other major components are updated.

[1] Microsoft Xbox One and Sony PlayStation 4. The Nintendo Wii U is another 8th generation console, but this study focuses on the Xbox and PlayStation due to their higher power draw and energy consumption.

[2] Microsoft Xbox 360, Sony PlayStation 3, and Nintendo Wii.

Game Console Energy Consumption

Game consoles consume energy in a number of modes, which previous work ([3],[4],[5]), has broadly divided into On (subdivided into Active and Inactive or Idle) and Standby (also Connected Standby or Rest Mode), based on whether the user is interacting with the console. Game consoles draw the least power in Standby Mode and the most in Active On Modes; however, the impact on annual unit energy consumption can be the opposite, due to the large portions of time spent in Standby Mode and the Inactive On Modes.

Furthermore, as the power draw in each mode can also vary based on the processor load and functions enabled, the U.S. Environmental Protection Agency (EPA), game console manufacturers, and other stakeholders developed a test method [6], ensuring there is no ambiguity. In this paper, we focused on the following modes, as defined in the EPA recognition criteria [7] and associated test method [6], which tend to have the largest impact on energy consumption.

1. Game Play Mode, where “a game is actively being played and the Game Console is receiving user input.”

2. Video Stream Play, where “a game console is playing a video stream through a network connection” (and also approximates playback of video from local sources such as optical disc or hard drive),

3. Video Pause Mode, where “the video player is paused during active streaming of the video”,

4. Navigation Mode, which “includes screen(s) initially displayed for user navigation”, and

5. Standby Mode, where the game console is “is plugged into a power source but is not providing any primary or secondary function and has no saved hardware state. The Game Console has no active network link although may be capable of charging devices in this mode.” [7] (However, 8th-generation high-power game consoles will maintain their network link when not providing other functions, remaining in a “Connected Standby” Mode, and it is this Connected Standby Mode that is used in the rest of the paper).

In addition, there are a number of other modes, from System Maintenance and Download Mode and Game Play Pause Mode [7], to TV Mode (pass-through and control of TV signals) [1] and Off Mode (completely turned off or unplugged, drawing 0 watts) [5]. These modes are not associated with primary functions but can impact annual energy consumption. A recent metering study found that game consoles spent 30% of the time in Off Mode [8], while another reported 34%, with 20% of units drawing 0 watts during the entire study period [5].[3] On the other hand another 10% were left on permanently in an Idle Mode, thereby increasing the average time in On Mode across the sample by a factor of three [5].

Figure 1, below, shows the power draw in three of the modes as measured through the years by Natural Resources Defense Council (NRDC). The data show that power in each mode increases at the beginning of a generation of game consoles as a more capable and therefore higher power consuming product is first released (e.g., PlayStation 3 compared to PlayStation 2). Subsequently, the power draw falls with each iteration within the same generation (e.g., PlayStation 3 2006 to PlayStation 3 2007).

[3] Although the study participants were recruited by energy efficiency organizations and may be more likely to unplug their game consoles or use a power strip to disconnect from mains, these findings will be used to develop usage profiles in the absence of other data.

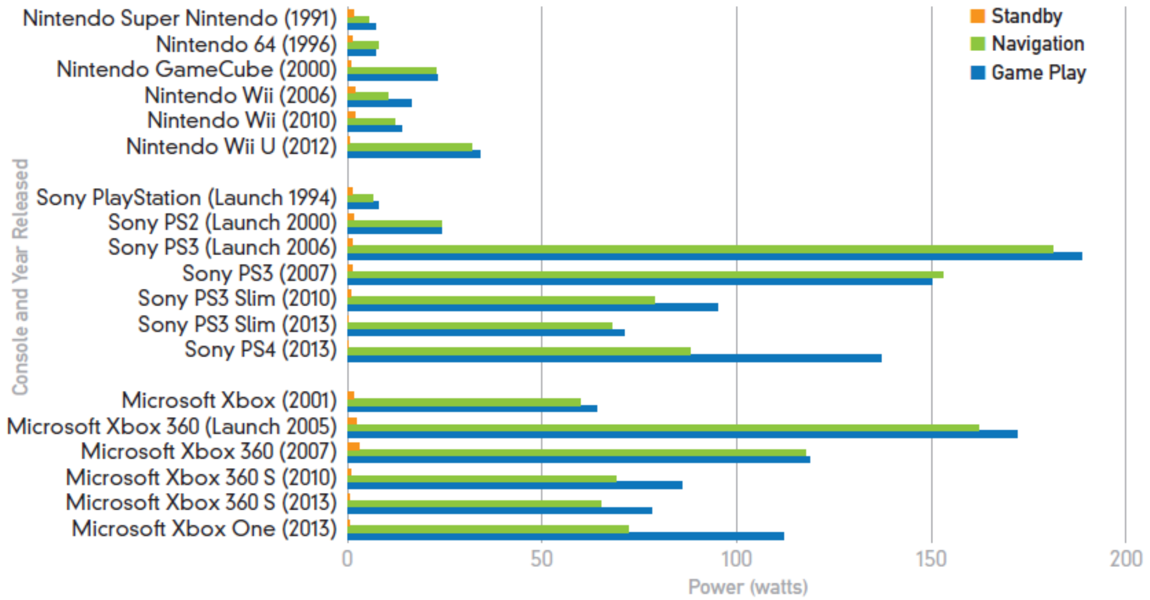

Figure 1. History of video game console power [1].

Semiconductor Industry Scaling Trends

This trend has been observed previously [3] and is mainly driven by updates to the integrated circuits (ICs, specifically logic and memory). The basic design of the ICs generally does not change within a particular generation of game consoles. The configuration and number of transistors is held constant, but the size of individual transistors decreases.

The same design with smaller transistors permit the ICs and the game console as a whole to use less power while ensuring compatibility with the same games. Throughout their lifetimes, Sony's PlayStation 3 (PS3) and Microsoft's Xbox 360 decreased the minimum feature size[4] of both the central processing unit (CPU) and graphics processing units (GPU) from 90 nm for both to 45 nm and 40 nm, respectively, as shown in Table 1. Similar trends occurred in memory ICs [9].

Table 1. Comparison of CPU and GPU technologies for game consoles. All data from references listed under Model unless referenced individually.

Model	Launch Year	Game-play Mode Power (W) [10]	CPU Line-width (nm)	Number of Transistors (million)	GPU Line-width (nm)	Power Supply Output Power (W)
PlayStation 2 [12]	2000	24.2	250	10.5	250	35 [13]
PlayStation 3 [14]	2006	188.6	90	234 [15]	90	380
PlayStation 3 [14]	2007	150.1	65	234 [15]	65	280
PlayStation 3 Slim [15]	2010	95.0	45	234 [15]	40	250

[4] The minimum feature size or linewidth is the smallest object that can be created in a semiconductor process and typically corresponds to the gate length of the transistor. This is the size of the gate as printed; nonidealities in the semiconductor process will reduce the gate to its "actual" or "physical" width. The minimum features size is also sometimes called the "technology node". [11]

Model	Launch Year	Game-play Mode Power (W) [10]	CPU Line-width (nm)	Number of Transistors (million)	GPU Line-width (nm)	Power Supply Output Power (W)
PlayStation 4	2013	136.5	28 [16]	N/A	N/A[a]	250 [17]
Xbox [18]	2001	64.0	180	21 [19]	150 [20]	100 [21]
Xbox 360 [22]	2005	172.0	90 [23]	165	90 [23]	150-203 [24]
Xbox 360 [25]	2007	118.8	65 [23]	165	90 [23]	150-203 [24]
Xbox 360S [26]	2010	86.0	45	372	N/A[a]	135 [24]
Xbox 360E [26]	2013	78.0	45	372	N/A[a]	120 [24]
Xbox One	2013	112.3	28 [25]	5,000 [27]	N/A[a]	135 [28]

[a] No GPU is listed as the CPU and GPU functions were combined in an accelerated processing unit (APU).

What drives this process is that smaller transistors permit smaller ICs. More of these smaller ICs can fit on a single wafer of silicon, so more can be produced in a given batch or per unit time. Furthermore, because there are now more chips on the wafer, proportionally fewer are right on the edge of the wafer, leading to fewer defects, and again lower costs [29]. Reducing the power of the processors also allows game console manufacturers to decrease the size of other components, such as power supplies, heatsinks, cooling fans, enclosures, and wiring, which saves additional money.

Traditionally, the shrinking of transistors in an IC permitted lower voltage and current. A shrink by a factor of k led to decrease in voltage by a factor of k as well as a decrease in current by a factor of k, which resulted in a decrease in switching power by a factor of k^2 [30]. In addition, there is also the leakage power that occurs when the transistors are not being switched.

Leakage power was small when Dennard proposed the scaling laws in 1974, but after 30 years of scaling, and corresponding reductions in the switching power, it became large enough to prevent further decreases in power through further Dennard, or “geometric”, scaling [31],[32]. Instead, designers have turned to “equivalent” or “functional” scaling, which is the use of new technologies, consisting of novel materials or geometric designs, to provide the same function but at a lower power and size. High dielectric constant (high-k) materials, transistors with multiple gates (FinFET) and other innovations have sustained progress in the industry. Although more gradual than geometric scaling, this trend is expected to continue as well as be augmented by new materials and processor designs better suited to particular applications [33],[35].

Power Draw Forecast for Current-generation Game Consoles (Xbox One and PlayStation 4)

The processors currently in use in both Xbox One and PlayStation 4 consoles are derivative of AMD’s Jaguar architecture, which is also used for personal computers (PCs) [36],[37]. Because of this overlap between game console and PC processors, we expect game consoles to be influenced by general computer industry trends. The scaling processes described above are expected to continue, leading to smaller, more efficient ICs in successive iterations of the Xbox One and PlayStation 4.

Power Use Model

To estimate the impacts of these industry trends on the power and energy consumption of game consoles, we developed a model of game console power draw that distributed the power draw in each mode among a handful of major components. The power draw of the components could then be varied with time based on industry forecasts to see the impact on total game console power draw and energy consumption.

The model is primarily top-down although it does include some bottom-up components such as power supply losses, and potential component savings. Including further bottom-up data, such as measured or theoretical power draw of components such as fans or processes such as video decoding could improve the realism of the model and we hope to include such granular data in the future. Even without these details the model tracks historical performance, as we will show toward the end of this paper.

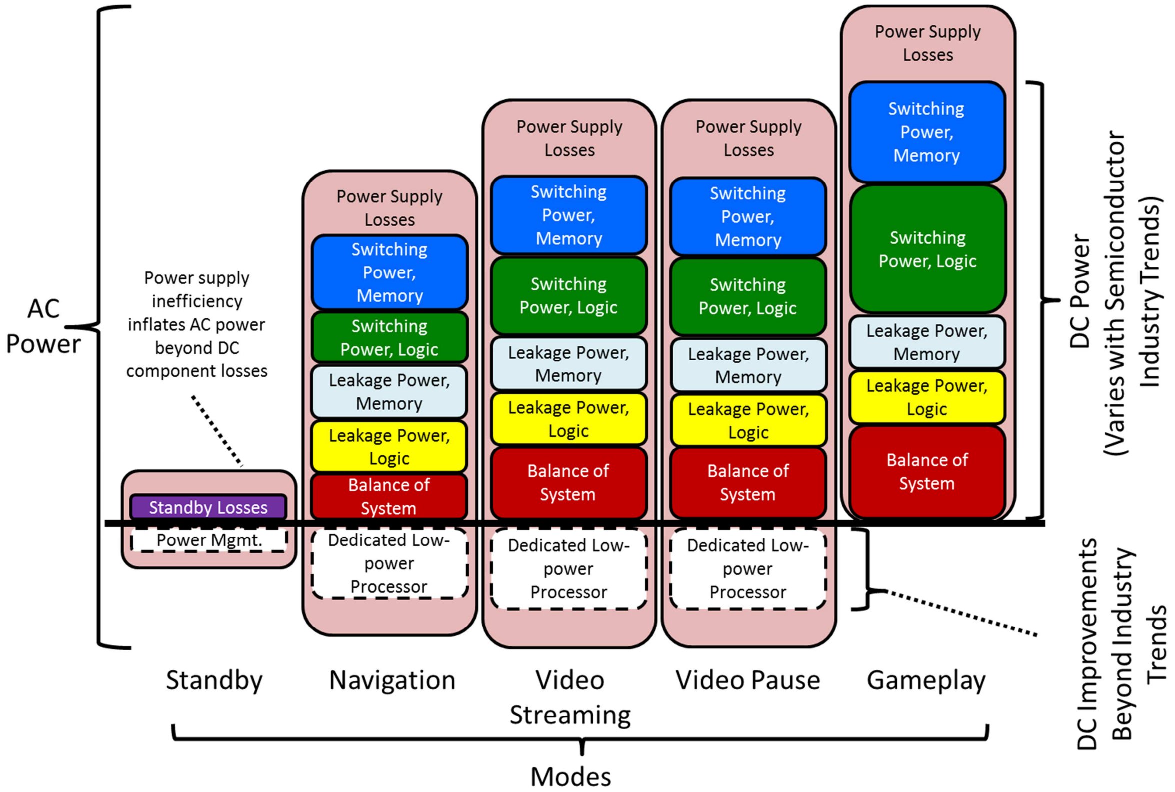

Figure 2. Illustration of the components of the model. Certain losses and improvements are held constant across modes, while others vary, such as switching and power supply losses. Not to scale.

As can be seen in Figure 2, above, we divided measured Standby power into a dc loss component, which includes all the functions powered in Standby (such as support for the Kinect component in the Xbox One), and a power supply loss component (ac-dc conversion). The On Mode allocations cover logic, memory, and other components of the system, which are operating in those modes.

The power supply losses are also different in the On Modes than in Standby due to the higher load on the power supply and therefore different efficiency. The losses were based on efficiency measurements of the 2014 Xbox One power supply with the game console in Gameplay, Navigation, and Standby Modes [2]. The Navigation Mode efficiency was assumed to apply to Video Stream Play and Pause Modes, and all these efficiency results were assumed to also apply to the PlayStation 4, for which power supply measurements were unavailable. The Kinect and total power draw in each mode were also based on test results (Gameplay: [10]; non-Gameplay: [2]).

The proportion of power attributable to logic and memory (switching and leakage) was based on forecasts in the 2011 edition of the International Technology Roadmap for Semiconductors (ITRS) [33], as described below. Finally, the power draw of the balance of components was estimated using data for a proxy PC with similar specifications as 8th-generation game consoles.[5]

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[5] The proxy computer featured AMD's A10 6800K (Kaveri) APU, micro architecture motherboard, 1x8GB memory, 500GB hard drive, Blu-ray Disc optical drive, and cooling fan. The power draw for each of these components was estimated using [34] under full load (representative of Gameplay Mode), in idle (Navigation and Video Stream Pause), and an average of the two (Video Stream Play).

Semiconductor Roadmap Inputs

The ITRS estimates logic and memory performance based on the expected trends in transistor and interconnect performance and design complexity. Based on these micro-trends, the ITRS projects power draw over multiple years as shown in Figure 3, below. This trend is increasing and shows what the processor of a next-generation game console could draw upon release in a future year, though ITRS notes that these power draw values are not at acceptable limits and there is a pressing need to develop new solutions to reduce power.

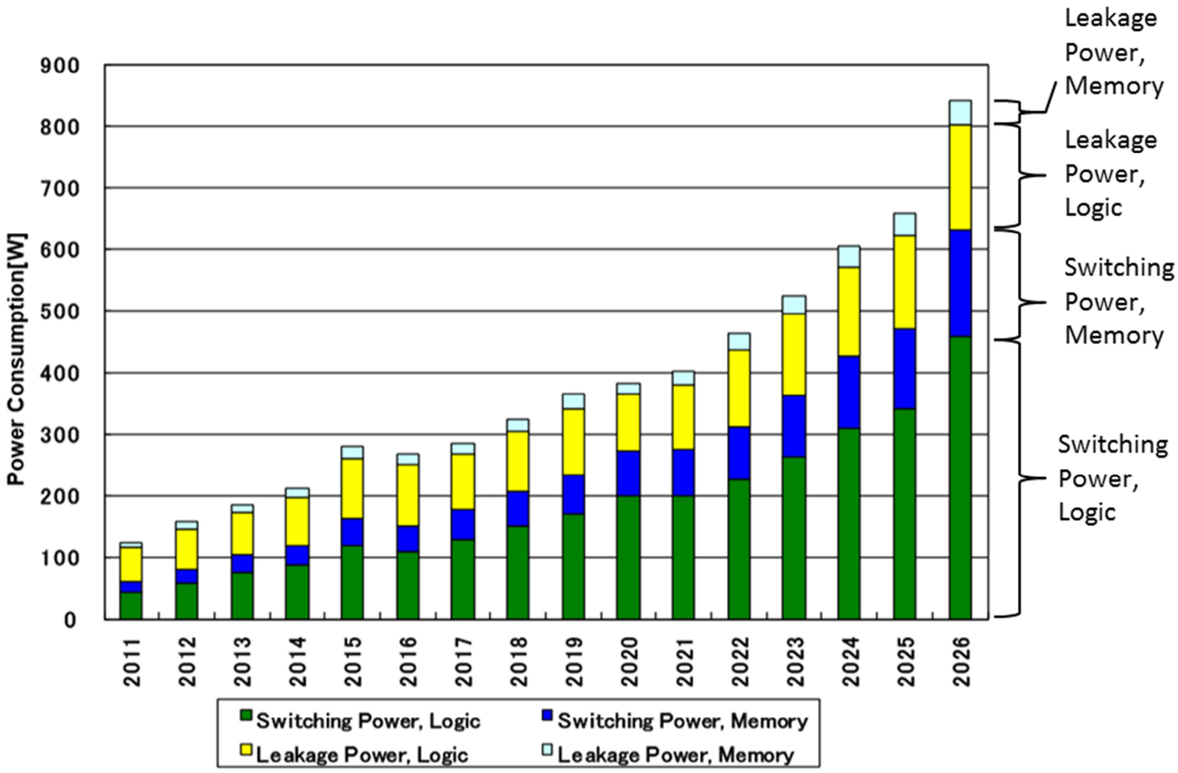

Figure 3. Switching and leakage power consumption trend for high-performance logic and memory, such as that in game consoles [38].

Although the power rises rapidly in Figure 3, not shown is the even faster rise in the number of transistors per chip, from 1.5 billion in 2011 to 49 billion in 2026 [38][6]. Were the number of transistors to stay constant—as it is expected to do through the life of a game console generation—the per-transistor and total chip power would decrease.

To estimate this decrease, we normalized the switching and leakage contributions for both logic and memory, illustrated above, to the typical transistor count in 2013. Although the APUs in the current generation of game consoles were developed in 2012 ([39],[40]), they use a 28 nm process, which the ITRS dates to 2013. Therefore 2013 was the base year for all calculations, the results of which are shown in Table 2 for logic and Table 3 for memory.

[6] The complexity of the logic portion of game console processors is measured in number of transistors. The memory portion is measured in terms of gigabits, which are forecast to grow from 69 in 2011 to 1,100 in 2026.

Table 2. Logic process characteristics and power inputs to scaling model.

Model Parameter	Source	2013	2014	2015	2016	2017	2018	2019	2020
Linewidth (nm)	ORTC Tables, from [38]	28	25	22	19.8	17.7	15.7	14	12.5
Number of transistors (million)	Overall Tables, from [38]	3,092	3,092	3,092	6,184	6,184	6,184	12,368	12,368
Switching Power , Logic (W)	Figure 3	70.8	83.7	115.9	106.3	125.6	148.1	167.4	196.4
Leakage Power, Logic (W)	Figure 3	66.0	75.7	96.6	95.0	88.6	85.3	103.0	90.2
ITRS Switching Power , Logic Trend Normalized to 2013 Number of Transistors (W)	Calcula-tion	70.8	83.7	115.9	53.1	62.8	74.1	41.9	49.1
ITRS Leakage Power, Logic Trend Normalized to 2013 Number of Transistors (W)	Calcula-tion	66.0	75.7	96.6	47.5	44.3	42.7	25.8	22.5

Table 3. Memory process characteristics and power inputs to scaling model.

Model Parameter	Source	2013	2014	2015	2016	2017	2018	2019	2020
DRAM ½ Pitch (nm)	Overall Tables, from [38]	28	25	23	20	17.9	15.9	14.2	12.6
Functions per Chip (Gbits)	Overall Tables, from [38]	69	137	137	137	137	275	275	550
Switching Power, Memory (W)	Figure 3	31.9	30.3	43.1	41.5	47.9	55.9	65.4	73.4
Leakage Power, Memory (W)	Figure 3	14.4	12.8	20.7	17.6	16.0	19.1	22.3	19.1
ITRS Switching Power, Memory Trend Normalized to 2013 Functions per Chip (W)	Calcula-tion	31.9	15.2	21.5	20.7	23.9	14.0	16.4	9.2
ITRS Leakage Power, Memory Trend Normalized to 2013 Functions per Chip (W)	Calcula-tion	14.4	6.4	10.4	8.8	8.0	4.8	5.6	2.4

One challenge is that increases in transistor count and memory complexity only occur every two or three years [38]. Therefore, during the in-between years, per-transistor power is increasing, and the power of a chip with a fixed design would tend to go up. We controlled for this by keeping the previous chip power between shrinks. This is equivalent to assuming that game console manufacturers would keep using the same chip until there is one available that draws less power. Although manufacturers would benefit from the lower cost of a smaller chip, waiting for a more efficient one permits them to also make the cooling fan and power supply smaller. The resulting trend for the contribution of logic and memory to processor power, normalized to 2013, is shown in Figure 4.

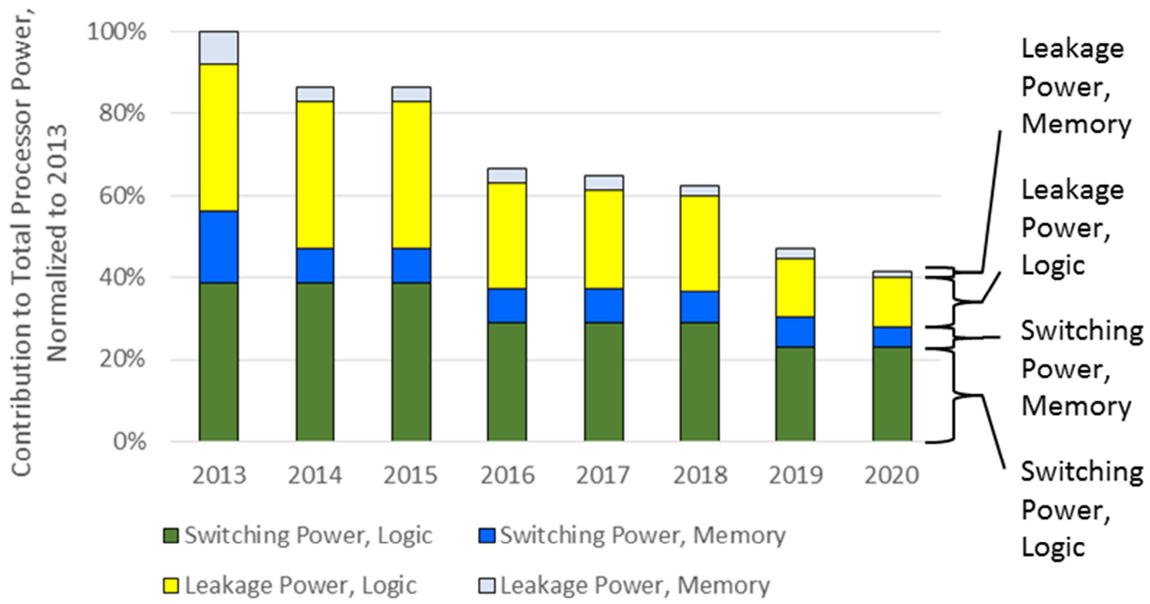

Figure 4. Relative switching and leakage power draw trend for logic devices and memory normalized to 2013 transistor and function counts.

It should be noted that although Dennard and functional scaling give a general idea of shrink and power draw at the transistor level, ICs will still vary in power draw even if they have the same number of transistors and feature size due to their design and operating conditions. For example, even though both the PlayStation 4 and Xbox One use similar APUs manufactured using the 28 nm process, they have different power draw in each mode. However, if each APU subsequently undergoes a shrink, equivalent decreases in power draw will be observed, and have been observed in the past (Figure 1). Figure 4 shows the expected decreases through 2020.

Model Results

After developing the normalized power draw trends for logic and memory leakage and switching power draw, we incorporated them into the game console model described earlier. We started with Gameplay Mode, where the processor is operating at a maximum and therefore where the ITRS data are most applicable.

In that mode, the measured power for the Xbox One, for example, was 112.3 W ac [1]. We subtracted out the power supply losses (17%) [2] and power attributable to other components such as motherboard, drives and cooling (45.4 W dc) to obtain 48.1 W dc. This is the portion of power draw that was ascribed to logic and memory and therefore subject to future scaling. We divided this portion between logic and memory and switching and leakage power using the 2013 proportions apparent in Figure 4: 39%, 36%, 17%, and 8%. In 2013, the proportions add up to 100%, as the contributions of each portion were normalized to 2013. However, as memory and processors improve with time, these proportions normalized to 2013 will decrease, and so will the total Gameplay Mode power.

For the power attributable to other components, it was assumed that the power draw will decrease at half the rate of the memory and logic. This was a compromise between holding it constant and scaling it per the ITRS, and reflects that transistors outperform most other components over time.

For other On Modes (Navigation, Video Stream Play, and Video Stream Pause), we subtracted out the power supply losses measured during Navigation Mode, the power attributable to other components, and the memory and logic leakage power calculated in Gameplay. The latter were assumed to remain the same between On Modes. Finally, we distributed the remainder among the logic and memory switching power, which would vary between On Modes.

This remainder ended up being a fraction of that in Gameplay Mode; however, the proportions between these fractional switching logic and memory proportions were assumed to be the same as in Gameplay Mode. For example, for the Xbox One the proportions in Navigation Mode in 2013 were estimated to be 17.3 W and 3.8 W for the logic and memory leakage power (same as for Gameplay Mode) and 1.1 W and 0.5 W for the logic and memory switching power (much less than in Gameplay, but the ratio between them remained at 2.2:1, same as in Gameplay).

We then multiplied the component power in 2013 by the proportions for each subsequent year shown in Figure 4 to project the effects of scaling through 2020, and summed the results to obtain the total power in each mode. Finally, a few additional improvements were added to the model manually:

1. A decrease in Standby Mode power to meet the following forthcoming requirements in Europe: 6 W by 2015, 3 W by 2017, and 2 W by 2019.

2. A decrease in Standby Mode power for the PlayStation 4 to reflect a 2014 firmware change that would stop charging controllers after a preselected time.

3. An increase in power supply efficiency to 60% in Standby, 84% in Navigation, and 86% in Gameplay to meet forthcoming U.S. DOE external power supply requirements (this was only applied to the Xbox One, as the PlayStation 4 has an internal power supply not subject to DOE requirements).

The results of these forecasts can be seen in Figure 5, which also shows the total annual energy consumption based on usage profiles for 7th generation game consoles. These are shown in Table 4, below. Until specific usage data can be developed for the Xbox One and PlayStation 4, these should be considered illustrative.

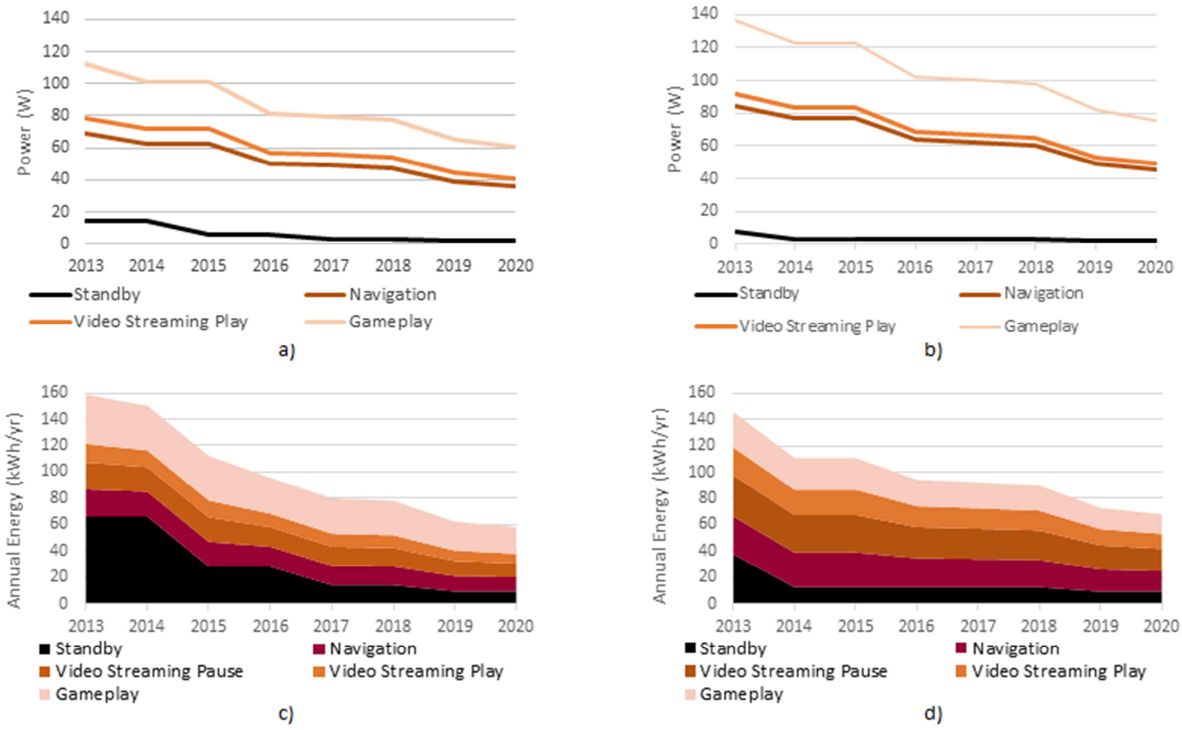

Figure 5. Forecasts of a) power for the Xbox One, b) power for the PlayStation 4, c) total annual energy consumption for the Xbox One, and d) total annual energy consumption for the PlayStation 4.

Note: Video Streaming Pause power is equal to Video Streaming Play power in the Xbox One and Navigation Mode power in the PlayStation 4, so it does not appear on the power graphs (a) and b)).

Table 4. Usage profiles for calculating annual energy consumption.

	Xbox Usage (h/wk)	PlayStation Usage (h/wk)	Source
Standby	90.1	90	Average Standby usage (Table 5 in [5])
Navigation	5.8	6.6	Half of Idle Time (Average usage per Table 3 in [5] minus active usage per Table 3 in [3])
Video Streaming Play	3.4	4.4	Proportion of time spent on all other activity per [39] times active usage per Table 3 in [3]
Video Streaming Pause	5.8	6.6	Remaining half of Idle Time
Gameplay	6.5	3.8	Proportion of time spent in Gameplay Mode per [39] times active usage per Table 3 in [3]
Total	**111.5**	**111.4**	Total does not sum to 168 due to Off/Unplugged Mode at 0 W (Table 5 in [5])

Validating the Model through Backcasting

As described in the previous section, our model of game console power and energy use relies on semiconductor industry forecasts for high-performance processors to forecast future consumption. Although the APU is the primary driver of power draw, there are many other components that contribute to the energy consumption, and which, in totality, can be significant. Using measurements, rather than the PC proxy, to model the current power draw and likely trends of cooling fans, HDMI driver, video decoder etc. would improve accuracy.

Similarly, although we do not expect the fundamental design of the game consoles and their APUs to change within the next five years, additional functions may be added, impacting the power draw beyond what can be forecast today. For example, the Kinect was introduced as an optional accessory with the Xbox 360, and was subsequently included with the Xbox One, affecting its power draw [2]. Similarly, Ultra High Definition video output or virtual reality headsets could increase power draw. Alternatively, accessories could add new modes which would not affect the power forecast in the existing modes, but could result in a real-world energy consumption significantly different from that forecast by the model. For example, encoding and uploading video during gameplay is not currently tested or included in the model, but is a popular activity and could become even more so in the future.

Given these limitations, can the model be trusted to provide reasonable forecasts of future power and energy consumption? To help answer this question, we put in logic and memory performance data from the 2005 and 2007 ITRS [9], and projected the impacts scaling trends predicted in 2007 would have on power in Navigation and Gameplay modes. We also factored in the Xbox 360 power supply efficiency [42]. We then compared the results of this backcast over 2005[7] through 2013 to contemporaneous measurements of 7th generation consoles performed by NRDC.

As now, it was not clear in 2007 whether the scaling trends would hold over multiple years or whether the game consoles themselves would not be redesigned to add functionality. As mentioned above, the Kinect was added, but as a separate accessory; meanwhile, one of the Universal Serial Bus (USB) ports on the Xbox 360 was removed in 2013, likely saving some power in all the modes [43]. Nonetheless, the backcast remained reasonably true to the historical power draw in Navigation and Gameplay Modes, as shown in Figure 6. The average error for these two modes across the three years when measurements were conducted was 14% for the Xbox 360 and 15% for the PlayStation 3, as indicated in Table 5.

[7] The Xbox 360 launched in 2005. Although the PlayStation 3 launched in 2006, it used a 90 nm processor, which the ITRS dates to 2005.

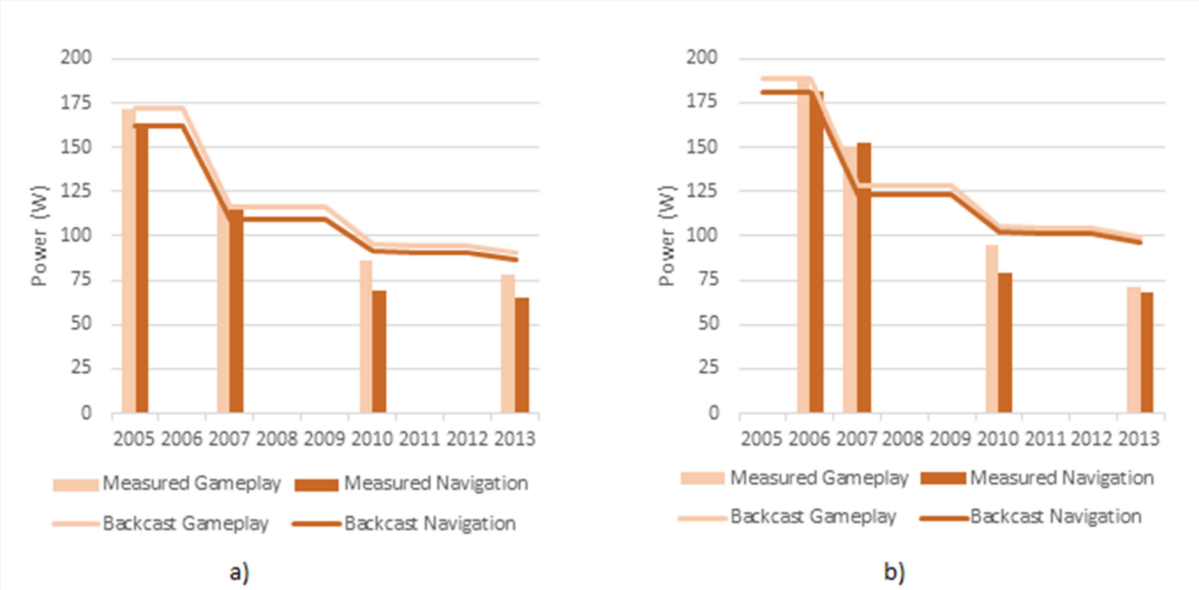

Figure 6. Backcast results compared to historical measurements for a) Xbox 360 and b) PlayStation 3. (Historical measurements from [10])

Table 5. Error between backcast results and historical measurements

	2007	2010	2013	Average
Xbox 360 Navigation Error	-7%	32%	33%	**19%**
Xbox 360 Gameplay Error	-2%	11%	16%	**9%**
Xbox 360 Average Error	**-4%**	**22%**	**24%**	**14%**
PlayStation 3 Navigation Error	-20%	29%	42%	**17%**
PlayStation 3 Gameplay Error	-15%	10%	40%	**12%**
PlayStation 3 Average Error	**-11%**	**20%**	**41%**	**15%**

Options for Further Efficiency

The previous two sections have shown large historical reductions in power draw and energy consumption within a generation of game consoles, and semiconductor industry trends that foreshadow a similar reduction in the current generation. However, even greater reductions may be possible using currently available technologies.

To estimate further energy reductions beyond the business-as-usual forecast (almost 50% reductions in Gameplay and other modes by 2020), we added the following improvements to the model:

1. Power supply efficiency: An 80PLUS Titanium power supply will be used, providing >90% efficiency in all modes, though this would be a costly upgrade;
2. Power supply output power reduction: As the console power draw decreases, so should the rated output power of the power supply, meaning that the power supply will be closer to its design optimum during normal operation;
3. All user-available energy saving settings are implemented by default, reducing power to less than 0.5 W in Standby Mode;
4. Xbox One Kinect is augmented with an occupancy sensor, reducing its power to 0.1 W in Standby Mode; and
5. A dedicated low-power secondary processor, similar to ones used in commercially available over-the-top set-top boxes is implemented to reduce power in Navigation, Video Streaming

Play, and Video Streaming Pause Modes to 5 W.

This may require a significant redesign in the case of the Xbox One. However, a secondary processor is already present in the PlayStation 4 and carries out many background tasks. Unfortunately, the APU remains active during video streaming to download the large files, resulting in high power draw [44]. However, if secondary processors are used for downloads as well as to perform all tasks that do not require graphics processing (i.e., all modes except Gameplay), lower power draws should be achievable.

We assumed that software changes could go into effect in 2015. However, hardware improvements could not be implemented until at least 2016. With the exception of the power supply, which is a factor applied to the total dc consumption within each mode, the improvements were modeled as a dc power subtracted from the dc draw occurring in that mode, resulting in a power savings. The effects of the improvements are shown for the Xbox One in Figure 7 and the PlayStation 4 in Figure 8, below.

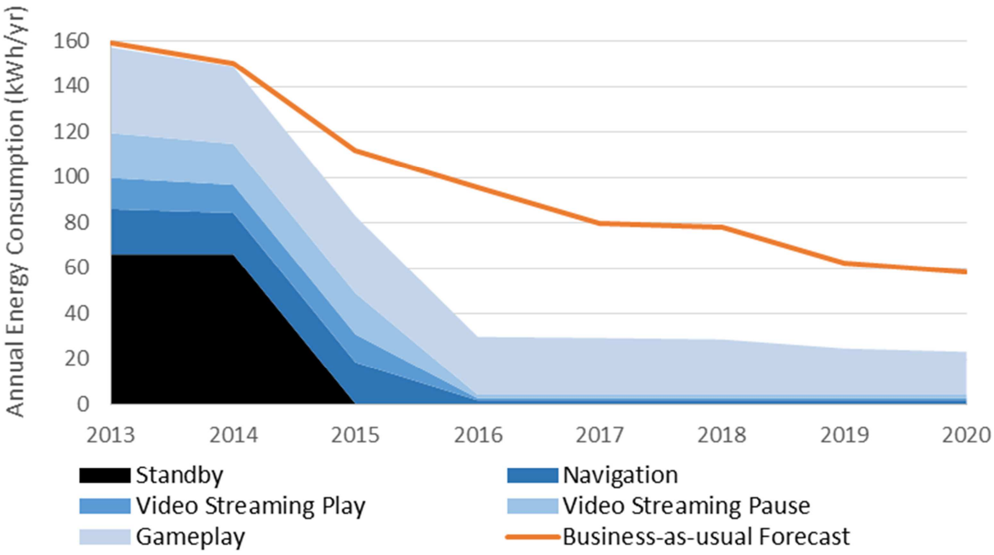

Figure 7. Forecast of annual energy consumption contributions of each mode following additional improvements, compared to business-as-usual, for the Xbox One.

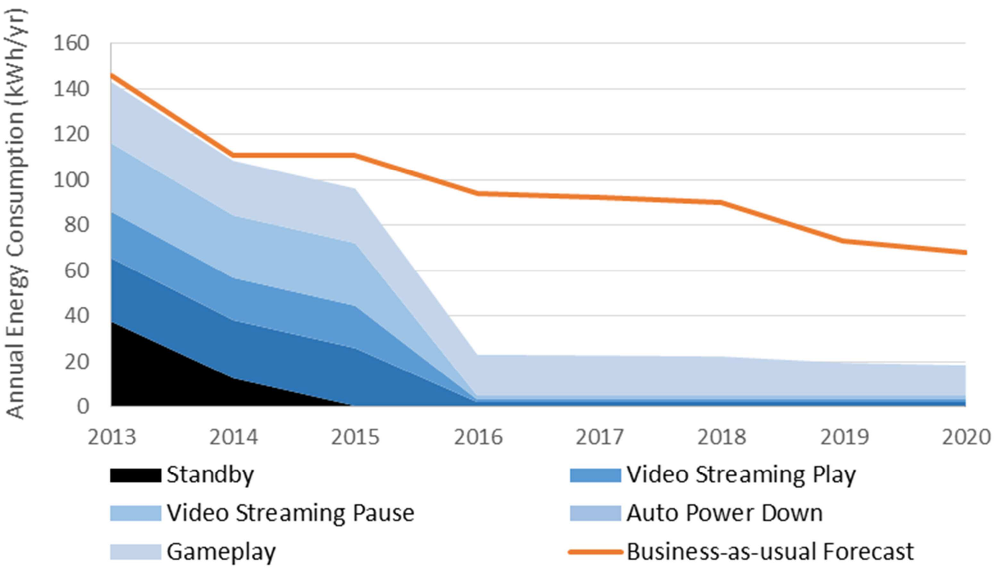

Figure 8. Forecast of annual energy consumption contributions of each mode following additional improvements, compared to business-as-usual, for the PlayStation 4.

As can be seen in the figures above, significant savings beyond business-as-usual could be achieved in the non-Gameplay modes by increasing power supply efficiency, implementing currently available energy saving settings, and providing dedicated hardware for video playback, comparable to over-the-top Internet Protocol set-top boxes. Total energy consumption could decrease approximately 90% by 2020, to 23 kWh/yr for the Xbox One and 18 kWh/yr for the PlayStation 4.

Conclusion

In this paper, we forecast a reduction in power and energy consumption for current (8^{th})-generation high-power game consoles: a 46% reduction in Gameplay Mode power and 63% reduction in annual energy for the Microsoft Xbox One and a 44% reduction in Gameplay Mode power and 53% reduction in annual energy Sony PlayStation 4, by 2020. The reduction is due to updated processors in subsequent iterations of these game consoles, and the expected hardware improvements is based on semiconductor industry trends that underlie performance improvements in in all areas of computing and are expected to continue into the future. Moreover, we showed that these trends also help explain the improvement in previous (7^{th})-generation high power game consoles, the Xbox 360 and PlayStation 3. Finally, we evaluated a series of improvements that could further reduce power draw in non-Gameplay modes, such as lower-power Standby and a dedicated processor for video playback, resulting in an annual energy reduction of 85% for the Xbox One and 87% for the PlayStation 4 by 2020.

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Results of the European Code of Conduct for Broadband Equipment

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Abstract

Broadband equipment is increasing its penetration in households and already contributes considerably to the electricity consumption of the residential sector in the EU. It has been estimated that in Europe for the year 2015, Broadband equipment is responsible for an energy consumption of about 50 TWh per year.

The European Commission JRC established in 2005 in collaboration with stakeholders (service providers, network operators, equipment and component manufacturers) the Code of Conduct for Broadband Equipment (CoC-BB), with the aim of limiting the energy consumption via the adoption of energy efficient technologies without hampering or limiting the service provided.

The BB-CoC covers equipment for broadband services both on the network side and on the customer side. On the customer side, it includes equipment for both the residential sector and Small Office Home Office (SOHO) applications, but not the terminals like, e.g., PCs or TVs. Most of the broadband equipment has a complete set of associated power targets.

The Code of Conduct is regularly updated in order to follow the fast technological development in this sector, with potential and concrete advantages compared to minimum efficiency standards set by regulation.

The paper, after an introduction to the principles, modus operandi and power requirements, presents and discusses the latest results based on the reports by the participating companies, and finally indicates possible improvement in the power allowances for the future.

Introduction

Total EU 28 electricity consumption in the period 2003 -2012 has grown by 4%. This increase has been driven mainly by electricity consumption in the residential and commercial (service), mainly due to the economic expansion of the sectors, the increase in cooling load, and the increased use of Information and Communication Technologies (ICT). In the commercial sector, annual electricity consumption in the European Union (EU 28) has increased in the period 2003 to 2012 from 698 TWh to 845 TWh, i.e. a growth of 21% while in the residential sector electricity consumption increased by 5%. The Joint Research Centre Energy Efficiency Status report 2012 (JRC 2012) has evaluated the ICT EU total annual energy consumption as 50 TWh, which is 2% of total EU yearly electricity consumption; at the time the ICT EU total annual energy consumption was projected to increase to 100 TWh (or 4% of yearly consumption) by 2020.

Van Heddeghem in his paper (Van Heddeghem 1) estimated the worldwide ICT electric energy consumption in 2012 as follows:

Total: 330TWh
Telecom operators networks: 256 TWh
Customer premises access equipment: 51 TWh
Office network: 23 TWh

The total EU electricity consumption in 2012 was 2884 TWh, while the total worldwide electricity consumption was 19443 TWh. Therefore the EU share of the total worldwide electricity consumption is 15%. 15% of the total ICT consumption worldwide in 2012, as estimated by Van Heddeghem, would be

50 TWh, perfectly in line with the JRC estimation. Most probably this is an underestimation as in the EU the tertiary and residential sectors have a higher share than in the rest of the world.

Why Broadband Equipment?

Electricity consumed in ICT equipment for broadband communication in the residential and small office sector is expected to contribute substantially to the electricity consumed in the European Union EU commercial[1] and residential sectors in the near future. It is therefore important that the energy efficiency of broadband equipment be maximised to ensure the mitigation of the carbon emissions and other impacts such as strain on infrastructure associated with increases in energy consumption.

In the EU there are policy actions for energy using products, in particular the European Eco-design Directive (2009), which introduces for all the EU Member States the same minimum efficiency requirements for end-use equipment such as domestic appliances, lighting products, consumer electronics, electric motors, air-conditioners, Uninterruptable Power Supplies (UPS), computers, servers, etc. In addition to the Eco-design directive, the EU has an agreement with the US on the shared use of the Energy Star labelling programme for office equipment. Energy Star programme is available in Europe, and it is promoted by public authorities as well as included in public authorities' procurement practices.

In particular, under the Eco-design, Regulation (EC) No 801/2013, there is an amending regulation introducing requirements for networked standby to the existing Regulation (EC) No 1275/2008 (with regard to eco-design requirements for standby, off mode electric power consumption of electrical and electronic household and office equipment), and to Regulation (EC) No 642/2009 (with regard to eco-design requirements for televisions). This is a horizontal implementing measure under the Eco-design Directive for networked standby. i.e. it applies to all the equipment for which there are no standby requirement in specific regulations. A networked standby condition which maintains a certain level of network connectivity but deactivates main functions could decrease overall energy consumption of such a product significantly. Networked standby contributes significantly to the electricity consumption as such equipment could not enable a deep standby as they need to maintain some communications capabilities to keep network presence and be able to respond to reactivation requests from network. Networked Standby consumption is estimated to be 90 TWh per year whereas the potential for cost-effective improvements are of around 40 TWh [NUS2011]. The Networked standby implementing measure is incorporated into the existing standby regulation 1275/2008 which implies that the horizontal approach is maintained. The implementing measure addresses household and office equipment as defined in 1275/2008 (professional equipment is not included) and complex TVs [NUS2001]. The Ecodesign requirements address availability of modes, power management, power consumption limits, and information to be provided by the manufacturers. The requirements are introduced in two stages[2]:

- From 1 January 2015: **12 Watt** for products with High Network Availability (HiNA) and **6 Watts** for equipment **without** HiNA.
- From 1 January 2017: **8 Watt** for products with High Network Availability (HiNA) and **3 Watts** for products **without** HiNA. This requirement does not apply to large format printing equipment.

The European Code of Conduct

In order to improve energy efficiency, policy makers have the choice between voluntary approaches and regulations. For sectors that are hard to regulate, e. g., for the

[1] The commercial sector is also referred as the tertiary sector and it includes both private and public buildings that host data centers. In this case energy consumption of data centers of companies in the industrial sector is included.

[2] HiNA equipment: Networked equipment with high network availability means equipment with one or more of the following functionalities, but no other, as the main function(s): router, network switch, wireless network access point hub, modem, VoIP telephone, video phone. Equipment with HiNA functionality: Networked equipment with high network availability functionality means equipment with the functionality of a router, network switch, wireless network access point or combination of them, but not being HiNA equipment. Network equipment: Equipment that can connect to a network and has one or more network ports.

very fast technological evolution or with several decision makers involved, it could be difficult to mandate efficiency requirements through legislation. In these situations, voluntary approaches such as voluntary agreement between public authorities and private enterprises could be more feasible and effective. Voluntary agreements have proven to be successful in improving energy efficiency in Europe in different sector (Rezessy 2012). Voluntary agreements have also been particularly effective in the case of the Energy Star programme for buildings and industry.

The market penetration and energy impact of ICT products are often subject to step changes driven by new technologies. Commercial secrecy about product development and marketing often makes the accurate prediction of these changes complex, if not impossible without the direct engagement and support of the key stakeholders involved in production and marketing. Where mandatory policy tools (such as energy labeling and Minimum Energy Performance Standards - MEPS), are introduced, engagement is often resisted, or is subject to protracted negotiation, because it is perceived by manufacturers as being imposed (Bertoldi 2005). In addition, at least in the European context, the legislative process for minimum efficiency requirements and mandatory labels is rather slow, and once a legislation is finally adopted it becomes difficult to change it. This is why, for fast changing technologies such as ICT (e.g., digital set top boxes - STBs), there is a preference in Europe for voluntary approaches. For STB and broadband equipment the power level, definitions and allowances need to be reviewed almost every year. These specifications can never be set more than two years in advance (we do not know how technology, demand and services will evolve over a longer period) and portions of the specifications become obsolete within 2 years. This makes the use of regulation introducing minimum efficiency requirements difficult, especially in the EU decision making context.

In Europe, voluntary programmes for the ICT sector called Codes of Conduct (CoC) have been introduced at the beginning of 2000. Currently, there are four Codes of Conduct in operation for ICT products: External Power Supplies, Digital TV Systems, Broadband Equipment and UPS. All these Codes of Conduct impose energy consumption limits or minimum efficiency levels for specific products in specific working modes. Participation by equipment manufacturers is on a voluntary basis, but when they join any of the Codes of Conduct they have to meet the performance level and report once a year on the energy consumption of the products they place on the market.

The Basic Mechanism of the Code of Conduct Policy Tool

The new rationale of the CoC policy tool is to proactively engage stakeholders, at the earliest possible stage of a product's commercial roadmap, in a voluntary scheme to mitigate the energy impact of the product without stifling product development and commercial objectives. This activity has become an excellent example of a product policy initiative that has united stakeholders early enough to impact the design process *before* the product became ubiquitous.

The following stages can be identified, and they will be discussed in the next sections:

- Stage 1: Identify priority products and set up working groups
- Stage 2: Improved energy efficiency criteria and CoC roadmap
- Stage 3: Achieved outcome, agreed with stakeholders
- Stage 4: Continuous review to identify best practices

Stage 1: Identify Priority Products and Set Up Working Groups

In Stage 1 of the development of the Code of Conduct, products with a potentially large market and high energy impact are identified by the European Commission JRC through reports and papers prepared by expert consultants. Products with the highest potential of impact on energy are prioritized and approaches are made to key stakeholders to contribute, on a voluntary basis, in working group discussions on practicable options to mitigate predicted energy impacts. The membership of these working groups requires adroit planning and negotiation:

- The working group must involve the main manufacturers of a product type. Manufacturer representatives should be in a position to act as a conduit to senior levels of product design and marketing.
- The interest and participation of major procurers, such as Service Providers, is essential since their endorsement of CoC objectives has a significant influence on product manufacturers. For example, the early involvement of major procurers of external power supplies in the Power Supply CoC Working Group (mobile phone manufacturers) resulted in the fast uptake of relatively stringent criteria through the use of efficient switching power supplies.
- A balance of independent experts and industry experts (e.g. from the Silicon[3] Industry) is required to evaluate the factors affecting energy efficiency performance, identify best practice and define practicable criteria objectives to mitigate the energy impact of the product in the marketing roadmap. Ideally some of these experts should have involvement in related technical working groups of standards bodies and industry association, in order to ensure a common approach to product testing that supports the discussions in the CoC working group.
- Political representation is important, to ensure that both national and EU-wide energy-efficiency objectives are fully considered; to provide practical support with CoC working group research and testing commitments through national agencies; and to catalyze endorsement, procurement and fiscal support schemes for products that meet the CoC criteria.

Stage 2: Improved Energy-Efficiency Criteria and CoC Roadmap

The principal aim of a working group is to reduce the energy consumption of a product through the setting of agreed achievable power requirement targets in a defined development timescale. To that end, a voluntary Code of Conduct is devised, and Europe's principal stakeholders in the products are encouraged to support the agreement.

The Signatories of the Code of Conduct[4] will make all reasonable efforts to:

- achieve the power consumption targets set for new products placed on the market after an agreed date, based on an agreed test method;
- support and contribute to the development and acceptance of new criteria based on the commercially viable application of "best practice" technology;
- co-operate with the European Commission and Member State authorities in an annual review of the scope of the Code of Conduct and the power consumption targets for two years ahead;
- facilitate and encourage consumers to adopt energy-efficient practices in connection with the use of services involving the product;
- co-operate with the European Commission and Member States in monitoring the effectiveness of the Code of Conduct; and
- ensure that procurement specifications for related services, systems, equipment and components are compliant with the Code of Conduct.

Stage 3: Achieved Outcome, Agreed with Stakeholders

The achieved and committed objectives of the CoC in a product area are disseminated to a global audience to promote common international energy efficiency criteria for the product types. It is important to notice that for the products covered by the two CoCs, there is a large degree of imports into the EU (almost 90% for external power supplies), and also a large similarity with products commercialized in other economic regions. Therefore there is a strong interest to have

[3] Throughout the text the authors use the term "silicon" to describe the semiconductor industry components in the product – since the principal functional blocks are embedded in LSI (Large Scale Integration) silicon chips.

[4] The list of the Signatories and the Codes of Conduct can be seen on the website of the EU Stand-by Initiative, the European Actions to Improve Energy Efficiency of Electrical Equipment while either Off or in Standby, at http://energyefficiency.jrc.cec.eu.int/html/standby_initiative.htm

similar energy efficiency policies and programmes in other regions of the world, to ensure more compliance to the CoC levels.

Stage 4: Continuous Review to Identify Best Practices

This aspect of the CoC mechanism is of particular importance. Expert input to the CoC working group must continuously review the potential for innovation in the technology to mitigate the energy demands resulting from increased functionality in the product. On a regular basis, relevant industry and independent experts are asked to review power requirement criteria for the basic products and for the power demands of the increased functionality dictated by product marketing.

In this context, the CoC for Digital TV identified a key tool for the achievement of significant energy efficiency targets in digital service system platforms - the development of effective power management in the silicon for the principal functional blocks.

The CoC power management task force, originally formed and supported by the UK Market Transformation Programme, has created a dynamic Silicon development "roadmap" which helps to qualify future revisions of the power requirement targets in the Code of Conduct. A range of power requirements in the standby passive, standby active and on modes are assembled for each functional block or group of blocks for which power can be managed. These values, qualified by the likely uptake time of the new Silicon or hybrid component (e.g. tuner) are used to agree on the timing and value of criteria updates. The task force relies on the cooperation of platform designers and silicon suppliers in the construction and continuous updating of this functional block roadmap..

A similar approach was also followed with manufacturers of broadband equipment, where the idle consumption has been dramatically reduced through discussions with all stakeholders.

Data submitted each year by stakeholders serves as an invaluable source of information to identify best in class products and industry trends in energy consumption. A careful analysis of this data provides a solid basis for defining future energy consumption allowances that can be challenging yet achievable by the industry. The reporting requirements are adjusted over time to facilitate the data analysis and improve this feedback mechanism.

The Broadband Equipment Code of Conduct

The BB-CoC covers equipment for broadband services both on the customer side as and on the network side. This Code of Conduct also covers the equipment for Small Office Home Office (SOHO) applications. The CoC contains a non-exhaustive list of equipment covered by the CoC, however it must be noted that not all the equipment listed in these tables may yet have a complete set of associated power targets. Additional technologies that become significant in the Broadband space may be added to future versions of the Code of Conduct. Figure 1 below gives examples of home gateway/modem configurations with the boundary between customer premises and network equipment that this Code of Conduct takes into account. Terminals for which there are specific Eco-design Regulations such as PCs or TVs are not covered by this Code of Conduct.

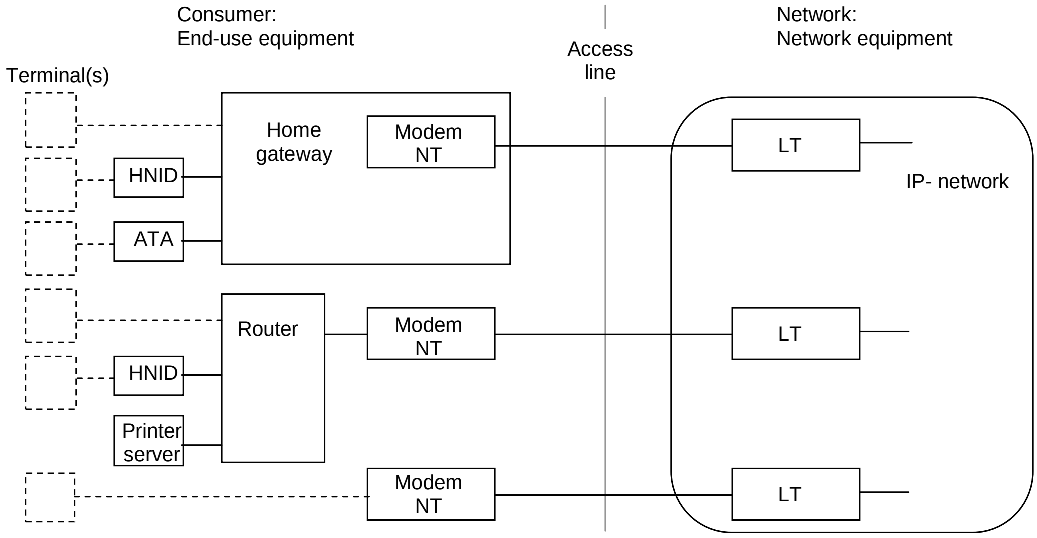

Figure 1; Examples of configurations

Results

Each of the participating companies (at the moment 14 European telecom companies and 6 large equipment suppliers) must report the power consumption of their new equipment covered by the Code of Conduct to the European Commission on annual basis. This should be provided by the end of each March for the previous calendar year. Anonymous results are discussed at least once a year by the signatories, the European Commission, Member States, and their representatives in order to:

a) Evaluate the level of compliance and the effectiveness of this Code of Conduct in achieving its aims.

b) Evaluate current and future developments that influence energy consumption, (i.e., Integrated Circuit development, etc.) with a view to agreeing actions and/or amendments to the Code of Conduct.

c) Set targets for future time periods.

Analysis

Based on the results reported by the participants for the year 2009-2013, the below graphs have been prepared for some key type of broadband equipment.

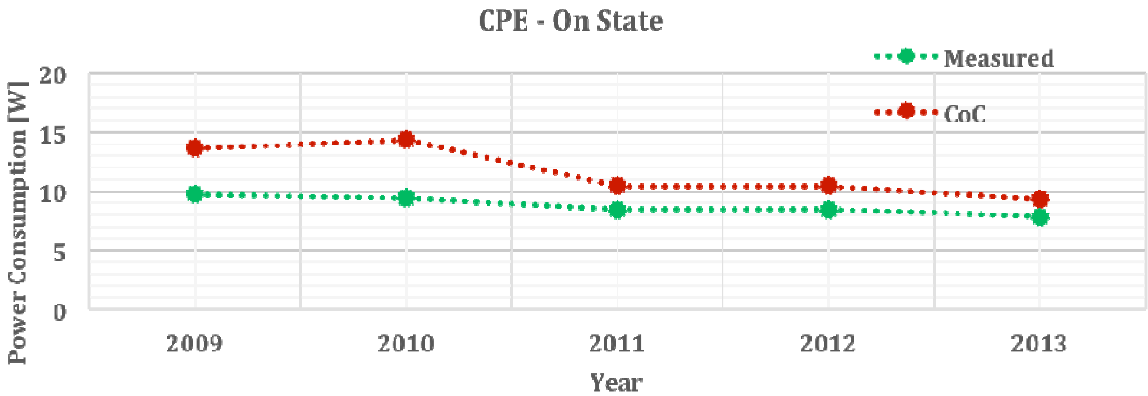

Figure 2: Average On state CPE power consumption and allowances for all submitted products of increasing complexity over time

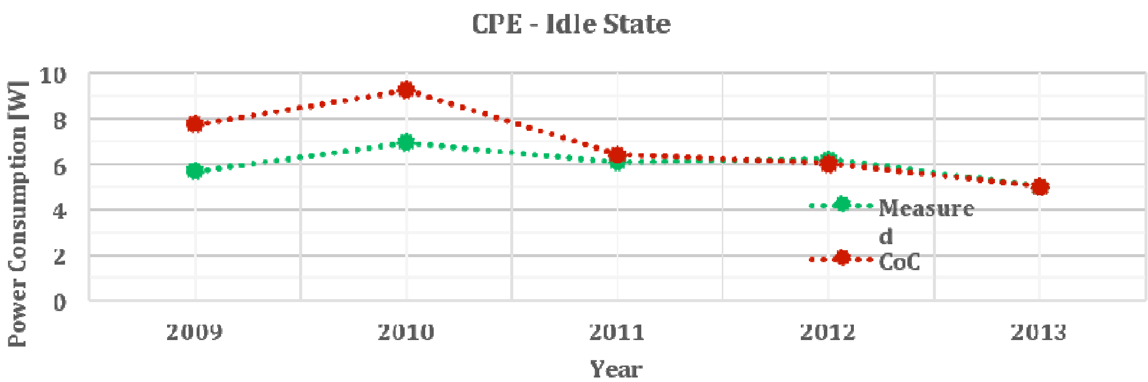

Figure 3: Average Idle state CPE power consumption and allowances for all submitted products of increasing complexity over time

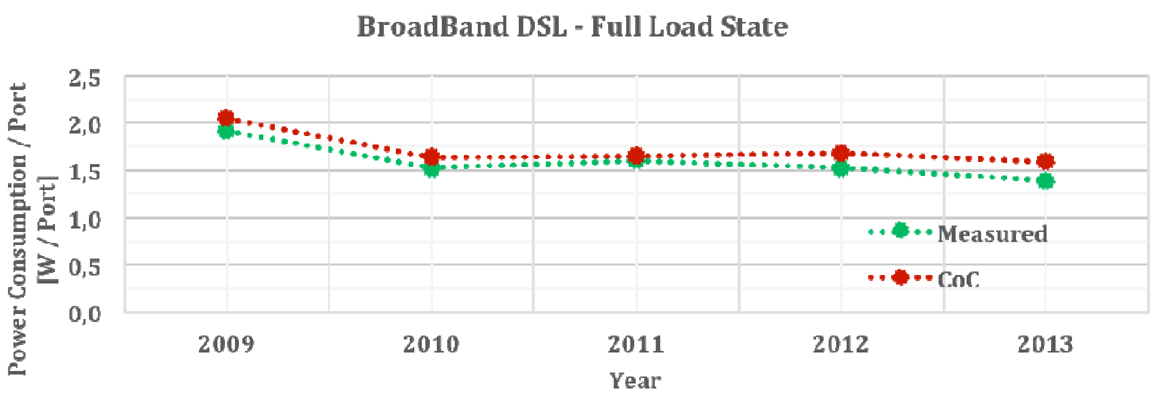

Figure 4: Network Equipment Full Load State per Port

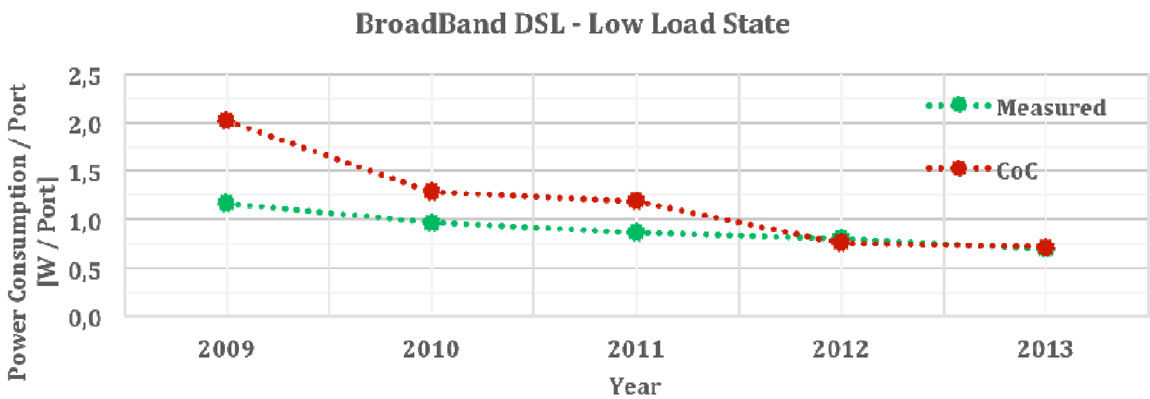

Figure 5: Network Equipment Low Load State per Port

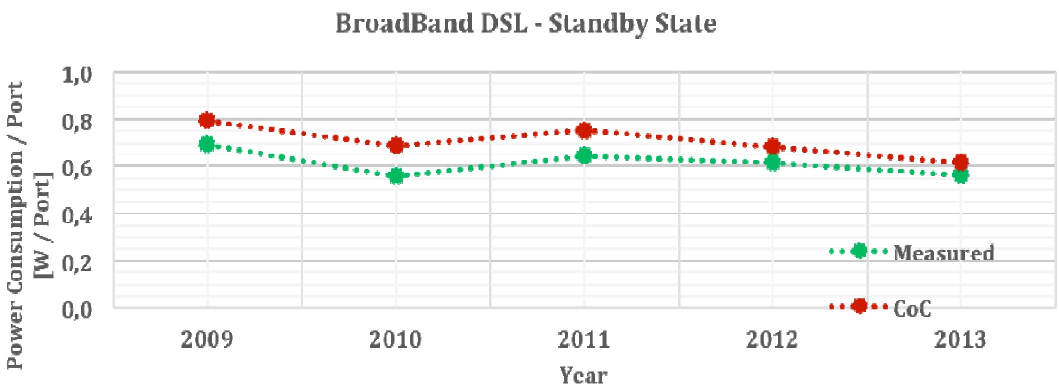

Figure 6: Network Equipment Standby State per Port

By analysing the above graphs it can be seen that for CPE there is only a moderate improvement over time of both the On State and Idle State power consumption. However over the period considered there has been an increase in the functions and interfaces for CPE, with equipment becoming more complex, and thus there is a real decrease in power consumption. For the idle State the average power consumption is very close to the CoC-BB limits, while for the On state the consumption is well below CoC-BB limits.

Looking in more detail at the 2013 reported data for CPE On State as shown in figure 10, it can be seen that not all the equipment is meeting the CoC-BB limits, with only 7% of equipment not meeting the targets[5]. If the same comparison is done using the 2015 targets, this share increases to 27%. In 2013 there was already 56% of the equipment with power consumption at least 20% below the required level, this share is down to 38% when using the V5 limits. The graph show that in 2003 there was already a "good" number (38%) of CPE meeting by a good margin (> 20%) the 2015 values.

[5] The CoC-BB requires each participant to meet the CoC levels with 90% of the products, considering the number of models produced (this is not based on sales, each models counts as one), therefore a number of reported products is expected to be above the CoC limits

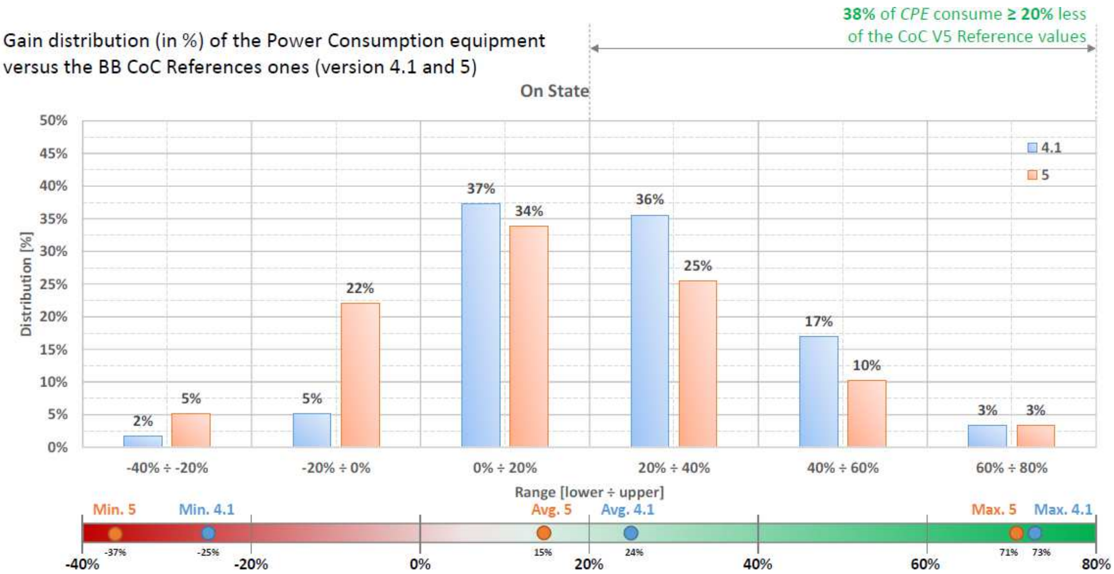

Figure 7: share of equipment consumption for CPE On State in relation V4.1 and V. 5 requirements

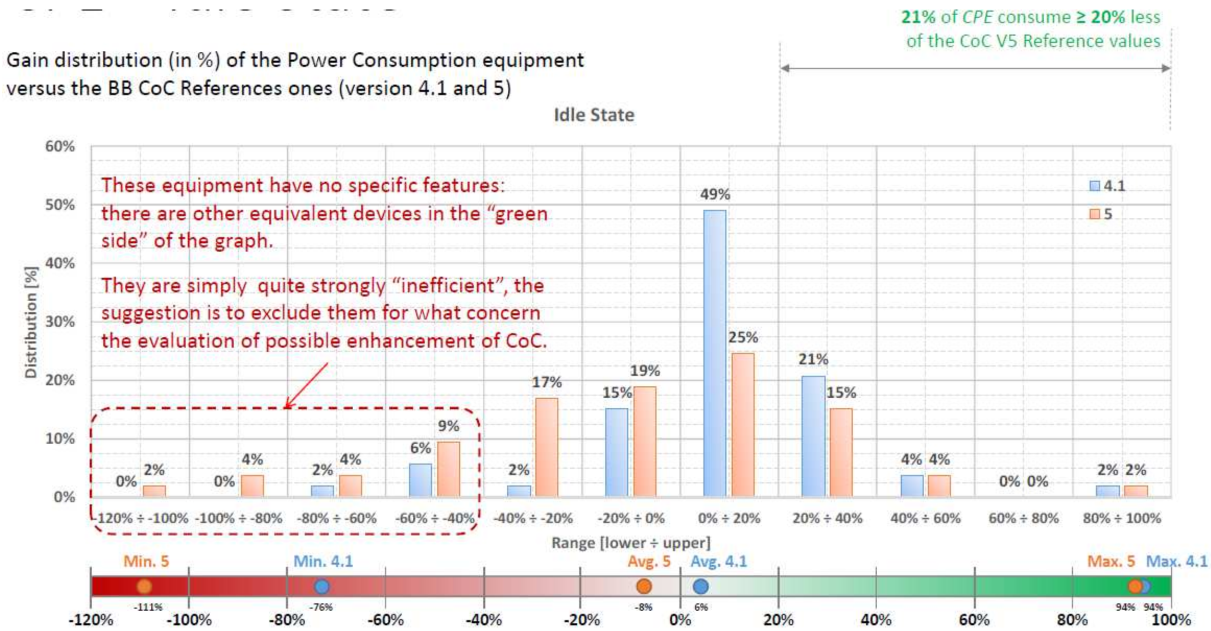

Figure 8: share of equipment consumption for CPE Idle in relation V4.1 and V. 5 requirements

For CPE Idle state the number of products not meeting the V5 limits is much higher (55%), while the share of products below the >- 20% is only 21%. This shows that most of the equipment is just meeting the limit, as also seen in figure 3.

For Network DSL equipment, the power consumption per port is decreasing both in Full Load state and in Low Load state.It is also important to note the for DSL network equipment most of the equipment is just meeting the requited level by a small margin

Conclusions

The Code of Conduct is a successful flexible policy mechanism to improve energy efficiency in broadband equipment as demonstrated by the large number of participants and the decreasing power consumption over time, despite the increased functionality.

The EU Codes of Conduct have served as an important platform for promoting energy efficiency in Europe. The Code of Conduct for broadband equipment covers both CPE and network equipment and every year new equipment is added to the list of the covered equipment. The Code of Conduct for broadband equipment has already reduced the energy consumption of this equipment, even if these offer many more features and services. Now energy efficiency is among the design priorities of next-generation equipment and in the procurement specification of service providers. The growing expansion of communication (e.g. for the cloud) to include digital TV and enhanced services such as HDTV and home networking will add further challenges for energy savings and climate change mitigation in the EU.

It is hoped that the Code of Conduct will make an impact on the power demand of these devices before hundreds of millions of them are sold. The European Directive on Eco Design offers an excellent platform for adopting effective minimum efficiency requirements. The major concern is the time needed to update Regulations compared to the fast technological development.

Last but not least, given the success of the Codes of Conduct in creating a useful stakeholder forum and in achieving concrete results in a very dynamic technological sector, the Code of Conduct could be used as a model for future policy development to include among the stakeholders not only the manufacturers, but also the service providers (in this case the telecom operators) and other stakeholders.

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European Digital Signage Markets - GfK Monitoring of Energy Efficiency via Standards and Labels

Author (Beate Diga)

Results of the Continuous and Precise Evaluation of the Technical and Economic Potential for Saving Energy - based on GfK Retail and Technology GmbH, Nuernberg, Point of Sale (POS)- and Distributor Panel Reporting 2014/2015

Abstract

We will focus on **European TV sales in consumer retail panel** and their development regarding Energy Efficiency in comparison to **"Digital Signage"- Large Format Public Display sales in Distributor B2B panel.**

This research focuses on the difference in energy consumption for both product groups and the identification of potential energy improvements for Digital Signage public displays.

The objective of this analysis with its economic and technical background is to provide information necessary to improve energy efficiency of different products. In the view of this GfK shows the efficiency of the labelling schemes for TV introduced in November 2011 ([1]) for mandatory use in the European Union. GfK also assesses the technical and economic background of the European market to evaluate how changes in such labelling schemes in Europe could influence new Digital Signage markets and accelerate the market switch towards energy efficient technologies.

The sales data used in the analysis represents international data and is provided by GfK Retail and Technology GmbH, Nuernberg.

[1] COMMISSION REGULATION (EC) No 1062/2010, it introduced the Label from November 2010 (mandatory from December 2011).

[2] Unless mentioned, all data related to TV hereafter is based on market sales data audited within the POS Retail Panel and B2B Distributor Panel by GfK Retail and Technology in 21 selected European countries, these are: Austria, Belgium, Denmark, Estonia, Finland, France, Germany, UK, Hungary, Italy, Latvia, Lithuania, Netherland, Norway, Poland, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland

1. Introduction of the two different GfK tracking levels (POS and Distributor)

GfK is a reliable source of relevant market and consumer information that enables its clients to make smarter decisions. More than 13,000 market research experts combine their passion with GfK's long-standing data science experience. This allows GfK to deliver vital global insights matched with local market intelligence from more than 100 countries.

By using innovative technologies and data sciences, GfK turns big data into smart data, enabling its clients to improve their competitive edge and enrich consumer experiences and choices.

Figure 1: GfK Retail and Technology's scope of services

*SKU: "Stock Keeping Unit", an SKU is a uniquely identified product by product numbers, and product identifiers.

1.1. International GfK POS Retail Tracking Panel *(figure 2 and 3)*

The term "retail panel research" defines the use of a panel (POS stores or distributors) to measure the sales of a product in a store for a time period to collect concrete facts, using a homogeneous system: GfK collects EPOS (electronical point of sale) data in regular intervals from a panel of retail outlets, which are selected and if necessary modified, to represent the current structure of relevant distribution channels.

The main static and dynamic objectives are to generate (static) quantitative sales data relating to a specific time period, and to reflect current (dynamic) market trends in terms of relevant market segments, product and price groups. It should identify both short and long-term changes in individual markets or market segments, so that retailer and manufacturer management is provided with an accurate information base.

Data from this retail panel shows retail consumer sales information including volume, value, price, and feature sets, etc. For defined product groups down to single item level. Statements regarding energy consumption in kWh are based on the mandatory Energy EU energy label for TV. In case of Digital Signage Displays we use the industry specifications (provided as self-declaration by manufacturers in industry specification sheets) on single model level.

In this way the data related to product features, product groups, sales and distribution structure can be clustered or analysed to make decisions on an empirical basis with regard to the planning, control and monitoring of market strategies.

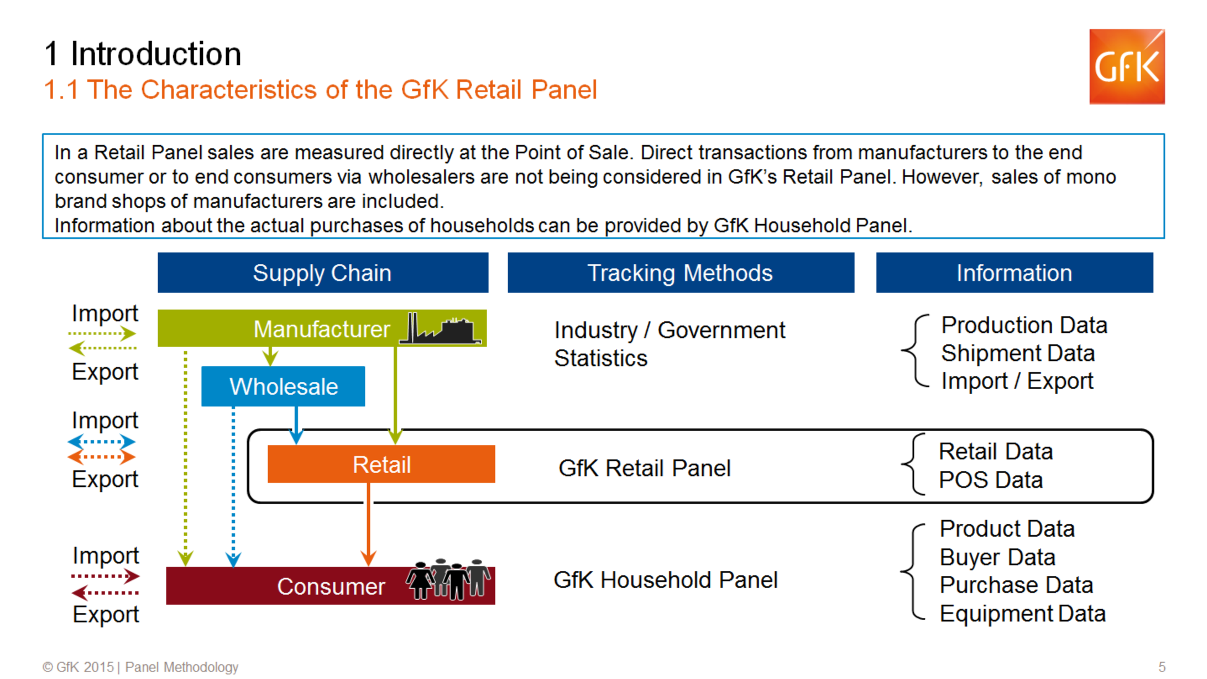


Figure 2: Characteristics of the GfK POS Panel (Retail Panel)

Figure 3: Examples for TOP retailer's cooperating with GfK in the POS/Retail Panel

1.2. International GfK Distributor Tracking Panel *(figure 4 and 5)*

Since 2014 the new GfK Distributor Panel covers 34 European countries and monitors **B2B Distributor sales** e.g. for Public Displays. It provides relevant information to support and accelerate potential energy efficiency improvements with regards to:

- Combining distribution, retail and reseller information into a single database with consistent reporting across 34 European markets segmented by regions, features, customers and price bands

- this universal view will make it much easier to identify improvements and efficiencies within the supply chain, to optimize performance or the distribution

- Market assessment with significant technological trends (market size, feature trends, brands with its impact on energy consumption). E.g. the large-scale transition towards LED or OLED technology and its impact on retributive trends like larger screen sizes and increasing product sales on total energy consumption

Direct industry sales to B2B Customers are not monitored within the distributor panel.

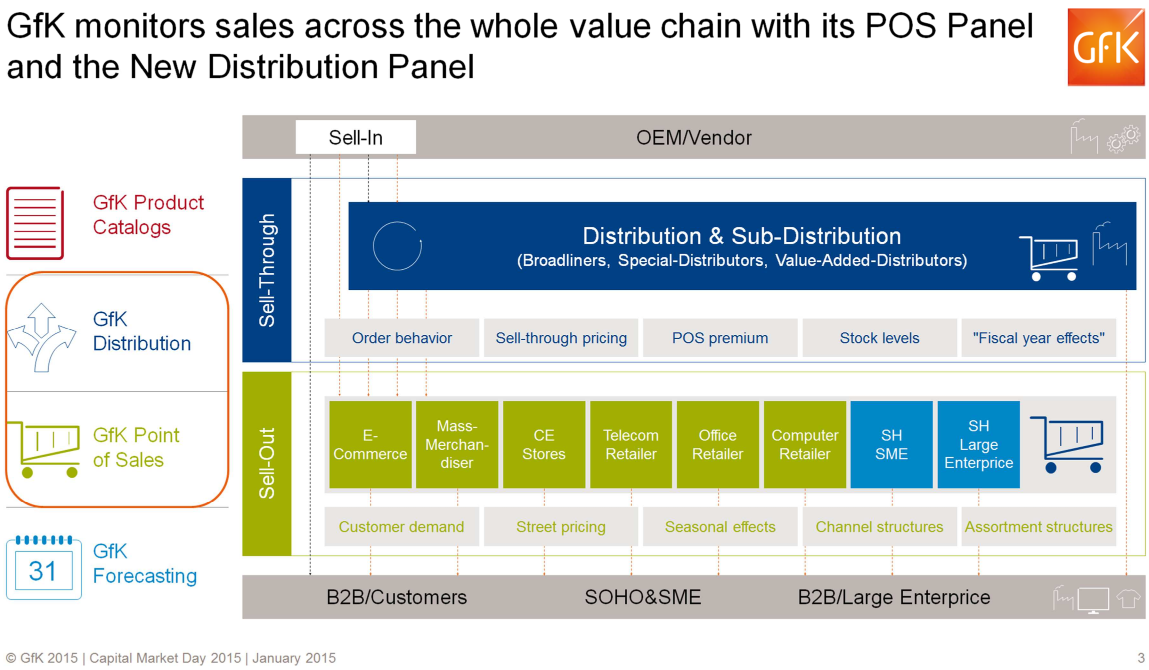


Figure 4: Characteristics of the GfK Distributor Panel

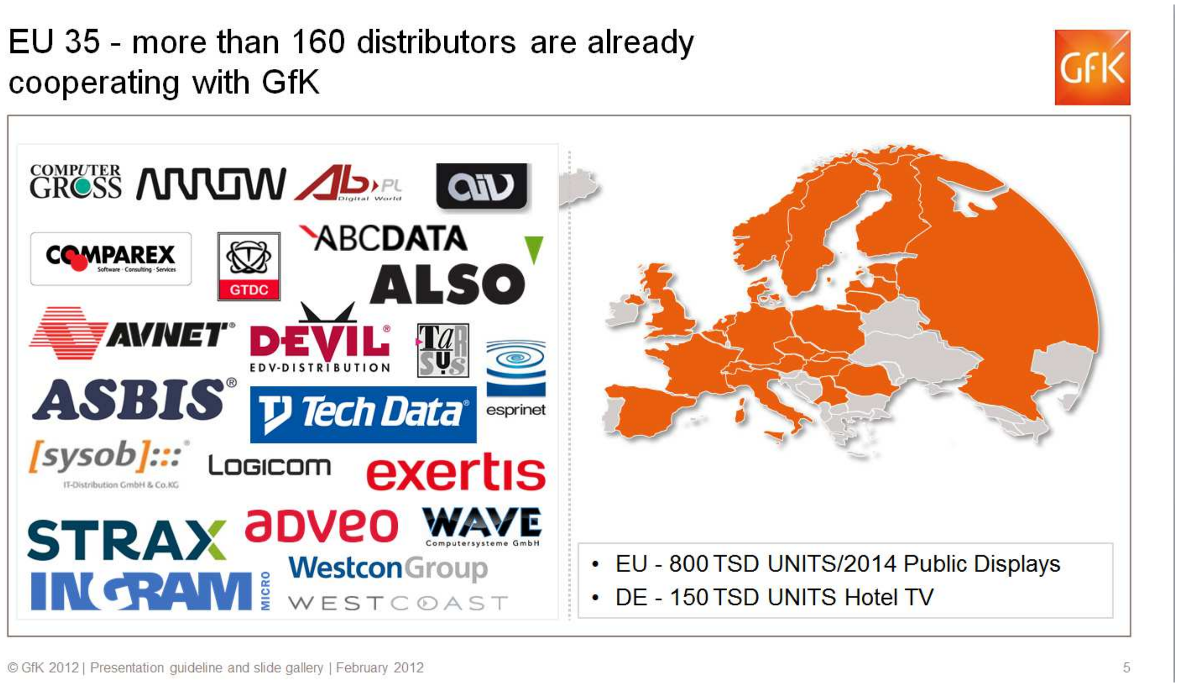


Figure 5: Examples for TOP distributors cooperating with GfK in the Distributor Panel

The To ensure the comparability of POS and Distribution data, new product groups in the POS Panel will be activated for the Distribution Panel as well.

Therefore, a process for adding new product groups or relocating existing product groups within the GfK Distribution Panel has been designed.

2. Further methodology and definitions of the paper

Country coverage

All figures regarding sales volume at POS or in B2B distributor sales mentioned in this work are based on the international GfK Retail and Technology panels in in 21 selected European countries, these are: Austria, Belgium, DK, Estonia, Finland, France, Germany, UK, Hungary, Italy, Latvia, Lithuania, Netherland, Norway, Poland, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland.

Energy consumption

All energy consumption related market information analyses are based on secondary statistics, namely the industry specifications (provided as self-declaration by manufacturers in industry specification sheets) on single model level.

Definition of Digital Signage Technology

GfK defined **Digital Signage Technology** in all analysis of this paper as any electronic display (with or w/o tuner) >= 32 inch sold via B2B channels that broadcasts television, information, advertising and other contents via digital signs utilizing technologies such as LCD, LED and plasma:

Objects of this survey are:

1. **Digital Signage Monitors (Public Displays) >= 32 inch B2B (GfK Distributor Panel)**

   Classified as “public displays” in industry specifications and sold in B2B channels

2. **Digital Signage TV >= 32 inch B2B (GfK Distributor Panel)**

   Classified as “Hotel TV” in industry specifications and sold in B2B channels

3. **Consumer TV >= 32 inch B2C (GfK POS Panel)**

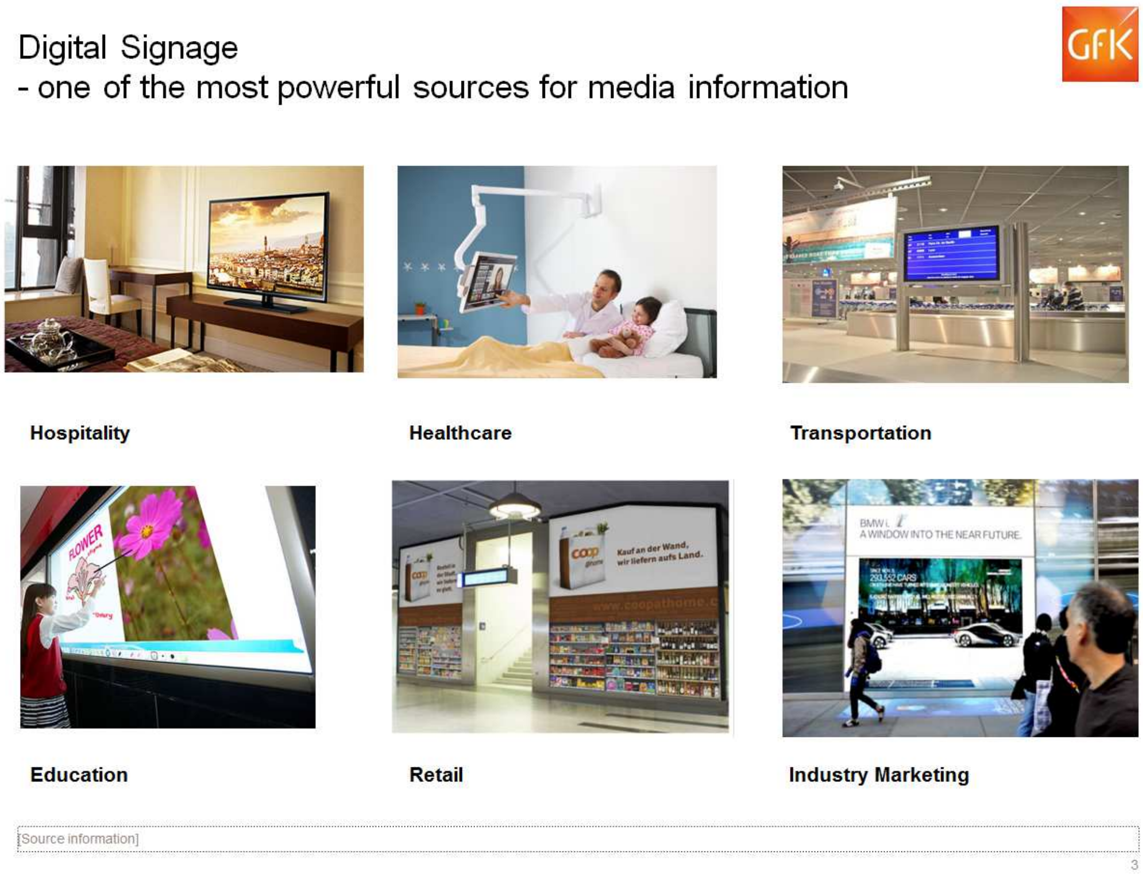
   Classified as Consumer TV in industry specifications and sold in B2C channels

   The energy consumption and Ecodesign attributes of Consumer TV are only used as a benchmark, but separately. As these devices are not part of the GfK Digital Signage definition.

Digital Signage Monitors/ TV's showing digital images, video, streaming media, information **in public places, retail stores, hotels, restaurants, corporate buildings, transportation hubs like airports, etc.**

Digital Signage displays use content management systems and digital media distribution systems, which can either be run from personal computers and servers or regional/national media hosting providers. Complete Digital Signage solutions consist not only of large format displays, but also media players, content management systems, device management consoles, wireless networking, security and cloud connectivity etc.

Creating and distributing content via digital signage requires ubiquity and streamlining ways to design, implement, and manage large system networks, which connect hundreds of signs to the back-end or cloud.



3. TV market assessment via POS Retail Panel in the context of the new European Energy label and Digital Signage market description with B2B Distributor panel sales

Sales for technical consumer goods are affected by many variables, such as economic development, technological trends or relevant policy instruments. In addition new lifestyle trends like online connectivity, changed communication behaviour, super large, UHD, OLED or curved or a growing number of Public Displays (Digital Signage) are redefining the role of the products with effects on viewing hours and total energy consumption.

Worldwide screen sales showed a growth of 192% between 2009 and 2014. The total sales are expected to reach 2,379 billion units in 2015.
Within this volume global LCD TV sales will continue to grow in 2015 in sales units, however due to negative price development no growth in value is expected. The price level in this technology dropped between 2008 and 2014 rapidly by 35 % (figure 6 and 7).

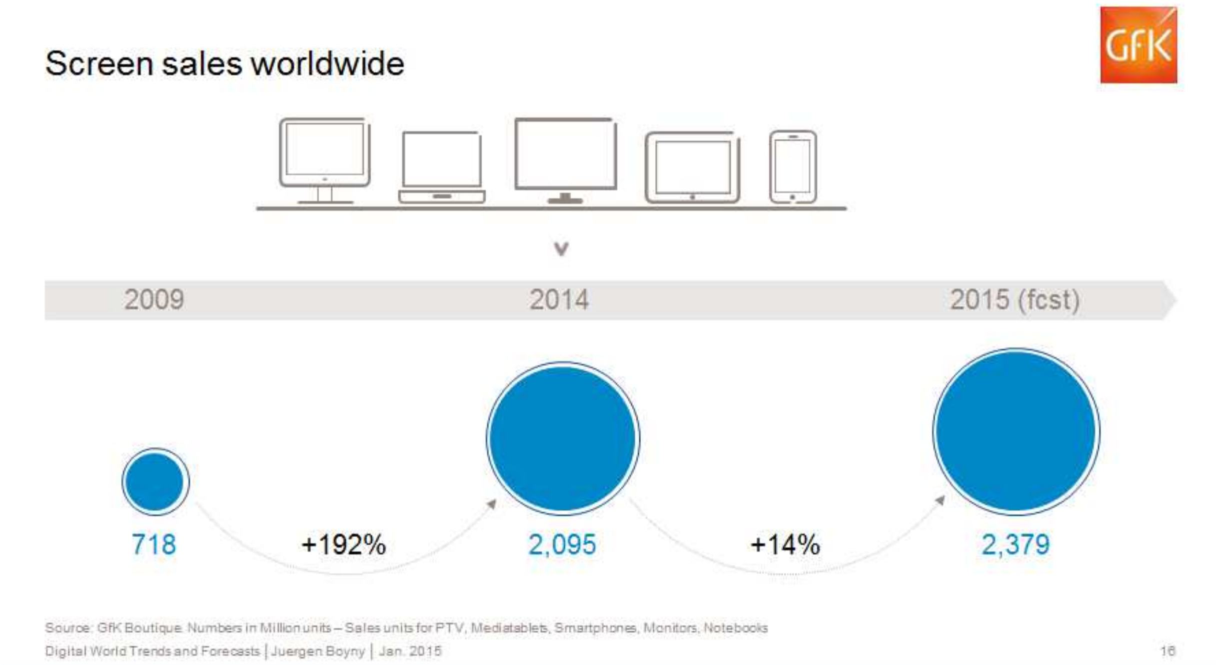


Figure 6: Worldwide volume of screen sales, Source GfK Retail and Technology in cooperation with GfK Boutique Research

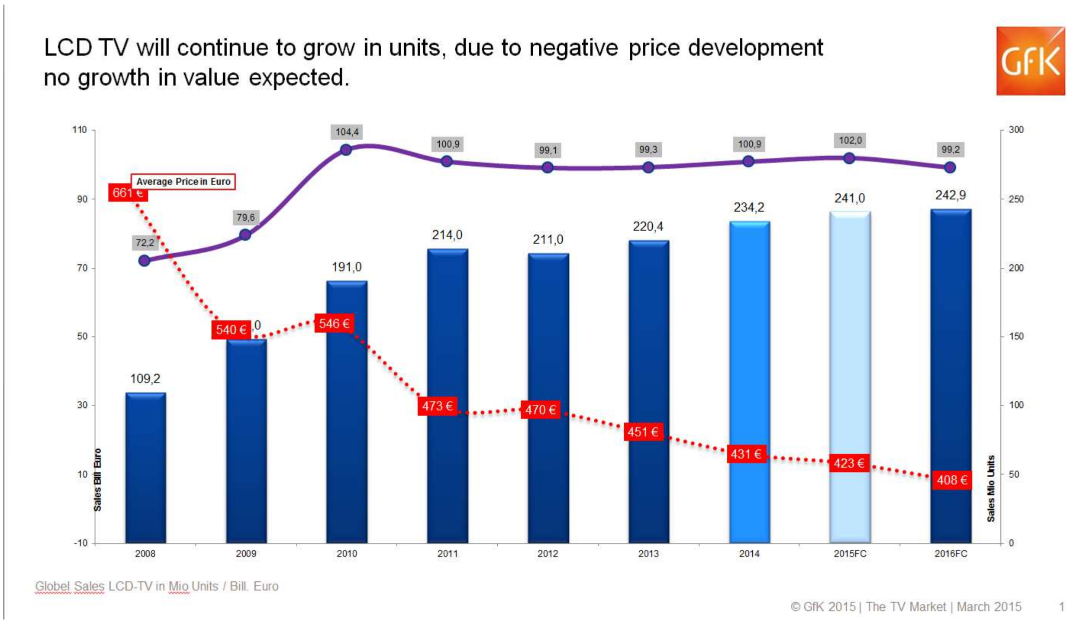


Figure 7: Worldwide LCD TV sales volume and price development, Source GfK Retail and Technology in cooperation with GfK Boutique Research

3.1. GfK POS Panel results for TV sales in consumer channels related to their cumulative energy balance

After the large scale transition to LCD TV followed by the rapid improvement of LED backlight technology and its impact on energy consumption towards an average consumption level of only 100 kWh/year (2012) the short term development in 2014 is still encouraging with a current consumption level of only 71 kWh/year *(figure 8 and 9) in EU 21.*

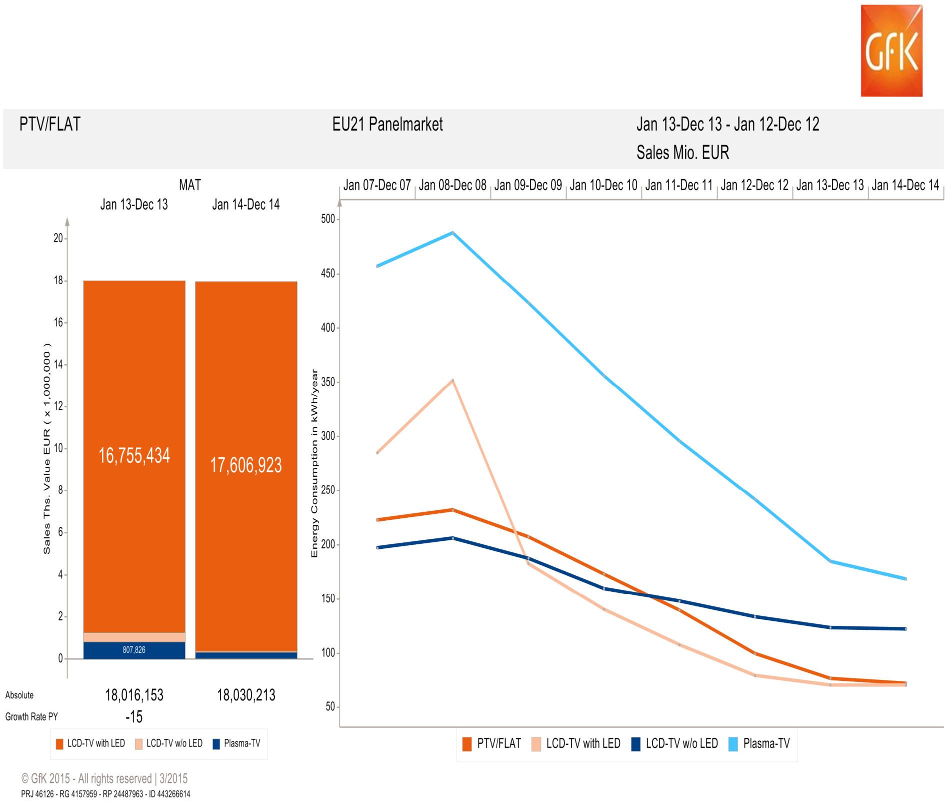


Figure 8: GfK POS Panelmarket sales for TV in EU 21 and the development of average energy consumption

In figure 9 the left side of the chart shows the development of TV sales volume by inch classes in EU 21. Volume peaks in the summer month (football world championship) and December (period with traditionally high retail sales volume). The inch classes 46 and above gaining rapidly market share – but the absolute energy consumption of these large screen sizes is much higher than for smaller TV Displays (left side of the chart).

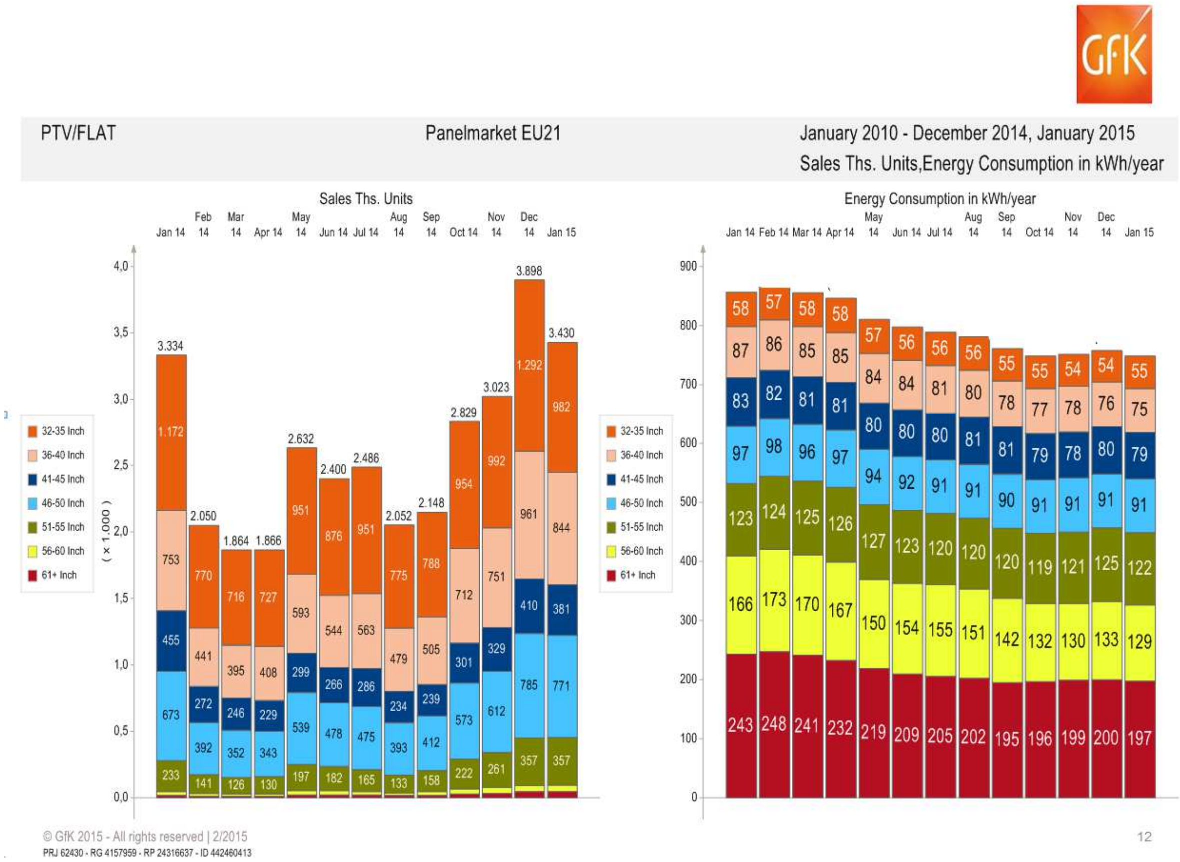


Figure 9: GfK POS Panelmarket sales for TV in EU 21 by inch classes between Jan 14 and Jan 15 related to the average energy consumption of those inch classes

3.2. GfK Distributor Panel results for Monitors and TV >= 32 inch sales in B2B channels related to their cumulative energy balance

Now turn our focus onto the rapidly growing market of digital signage including applications for B2B retail, healthcare, transportation, education and others who utilize the technology for various purposes such as way finding, communication, advertising and promotion, at point of sale (POS) or point of transit (POT) or general infotainment in leisure activities.

The GfK Distributor Panel monitors B2B sales of Public Displays (Digital Signage) and TV (classified as Hotel TV) since January 2014. The GfK distributor panel covers appr 50% - 60% of the Total Digital Signage market as direct industry sales are excluded.

The reported market in figure 9 shows a growth of appr 10% in volume and value sales for Public Displays 32+ Inch in March 2015 vs 2014. *(figure 10)*

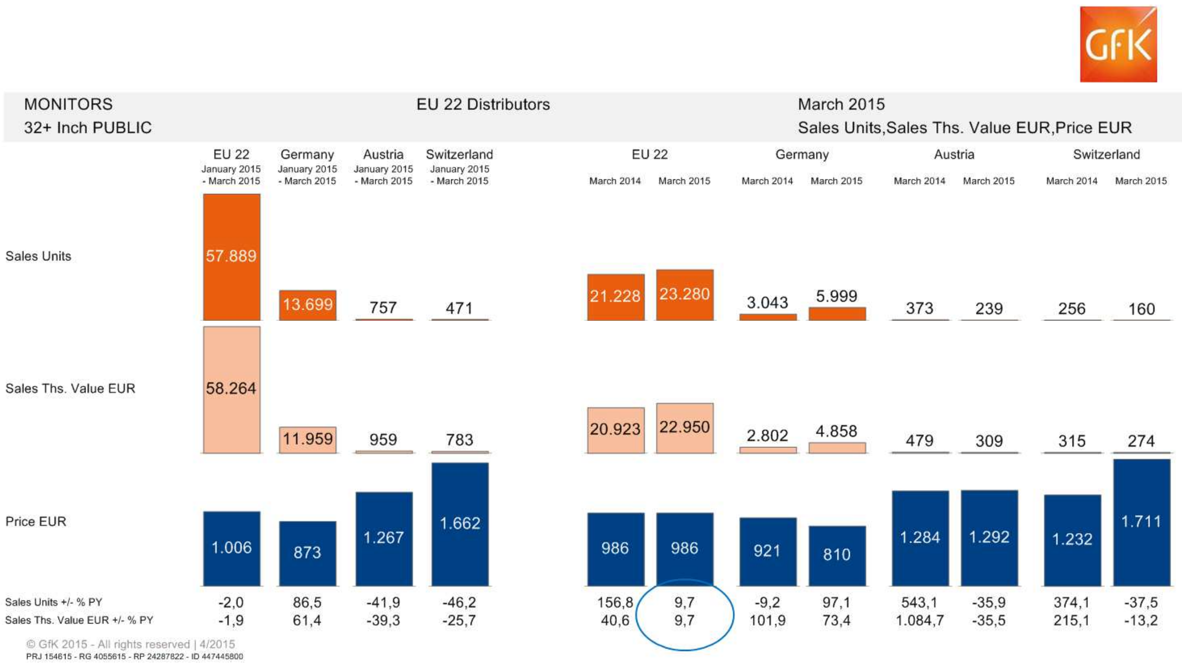


Figure 10: GfK Distributor Panel sales for Public Displays in EU 22 with average prices and market growth in March 2015 vs March 2014

EU 22 = Austria, Belgium, Denmark, Estonia, Finland, France, Germany, UK, Hungary, Italy, Latvia, Lithuania, Netherland, Norway, Poland, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland, Russia

In the graph below we compare the energy consumption of monitors >=32 Inch B2B (digital signage; blue line) with TV >=32 Inch Consumer sales (red line) ceteris paribus (on-mode power (W) x 4 h x 365d) (Figure11) the **results leads to a significantly higher energy consumption for digital signage monitors** (blue line).

Further on the difference in energy consumption seems to increase if we analyse these products in regard to Inch classes – the gap in discrepancy becomes more significant.

The average difference across all Inch classes shows that the average energy consumption (kWh/year) of B2B digital signage monitors in comparison to Consumer TV is 40,3% higher.

However, the higher energy consumption in case of Digital Signage monitors => 32 Inch depends primarily on technological requirements like outdoor illumination, etc.

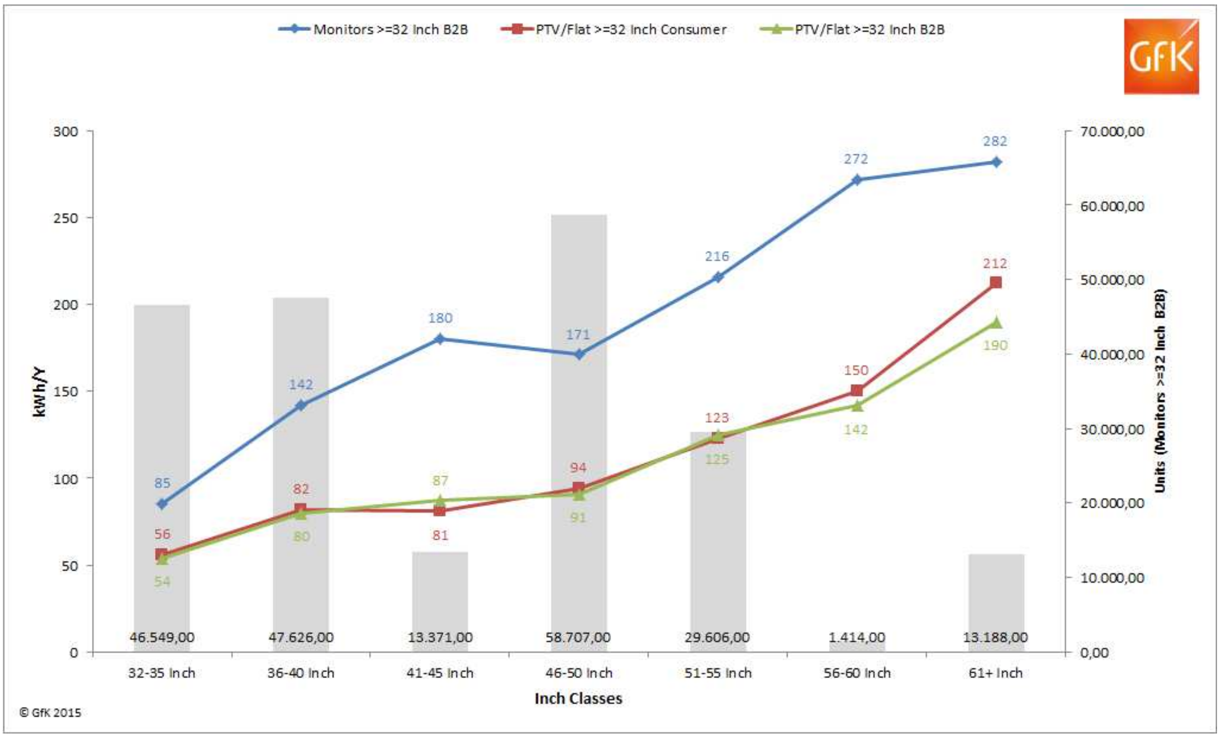


Figure 11: Comparison of the energy consumption of monitors >=32 inch sold in the Distributor Panel (Digital Signage; blue line) with TV >=32 Inch POS retail sales (red line)

All energy consumption figures for Digital Signage are based on industry specifications (provided as self-declaration by manufacturers in industry specification sheets) on single model level.

Provided that B2B Digital Signage monitors operate with a running time of "24/7" we extrapolated energy consumption data in figure 11 from 4h/day to 24h/day.

The average energy consumption shows in that way an even higher impact with a tremendous difference in energy consumption and supports definitively a full realisation of energy efficiency potentials and necessity of mandatory environmental requirements for displays (figure11).

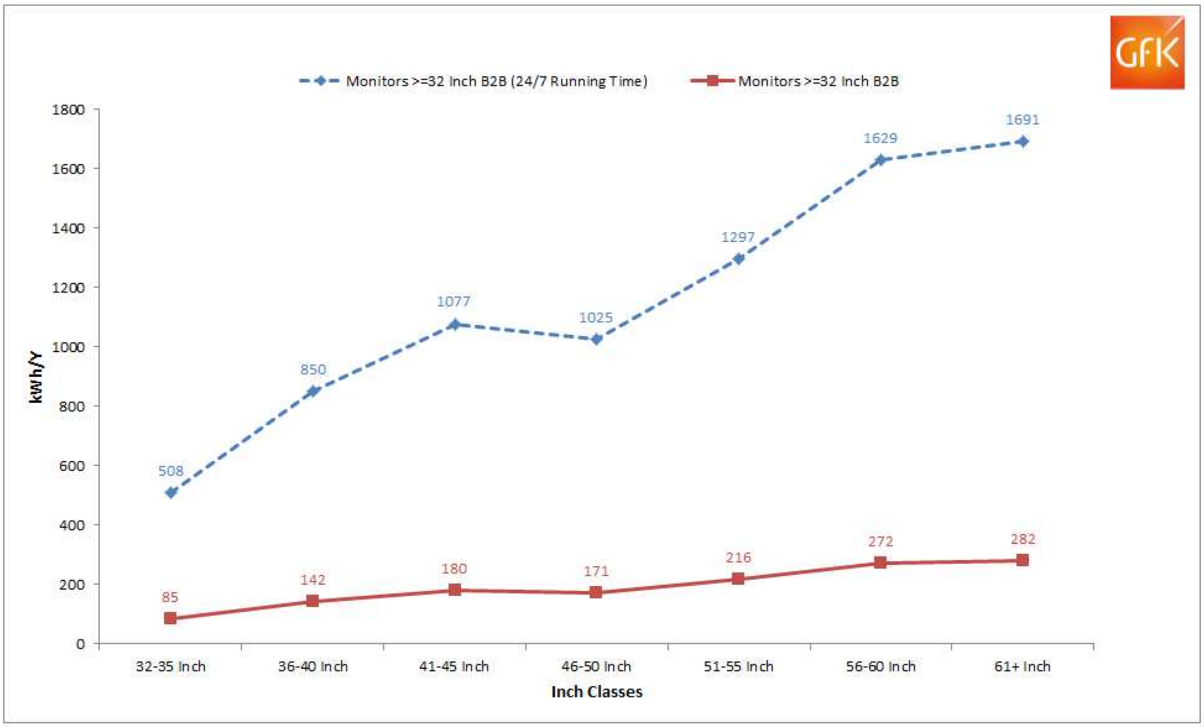


Figure 12: Extrapolation of the energy consumption data of monitors >=32 inch sold in the Distributor Panel (Digital Signage) "from 4h/day to 24h/day"

4. Current distribution of the TV Energy Label in Europe

In the very fast processing display technologies GfK enables easily to review and control the requirements and importance of the different energy efficiency classes with country specific developments to make these trends transparent.

3 years after the introduction of the mandatory TV Energy Label 87,7 % of the products use label A, A+ and A++. Products within category B, C and D with less than 5% of the volume are underrepresented or missing completely. (figure 12)

Further on larger products with higher absolute energy consumption shall not achieve easier good Energy Efficiency classes than smaller products. The absolute consumption in kWh/year is the criteria with higher importance.

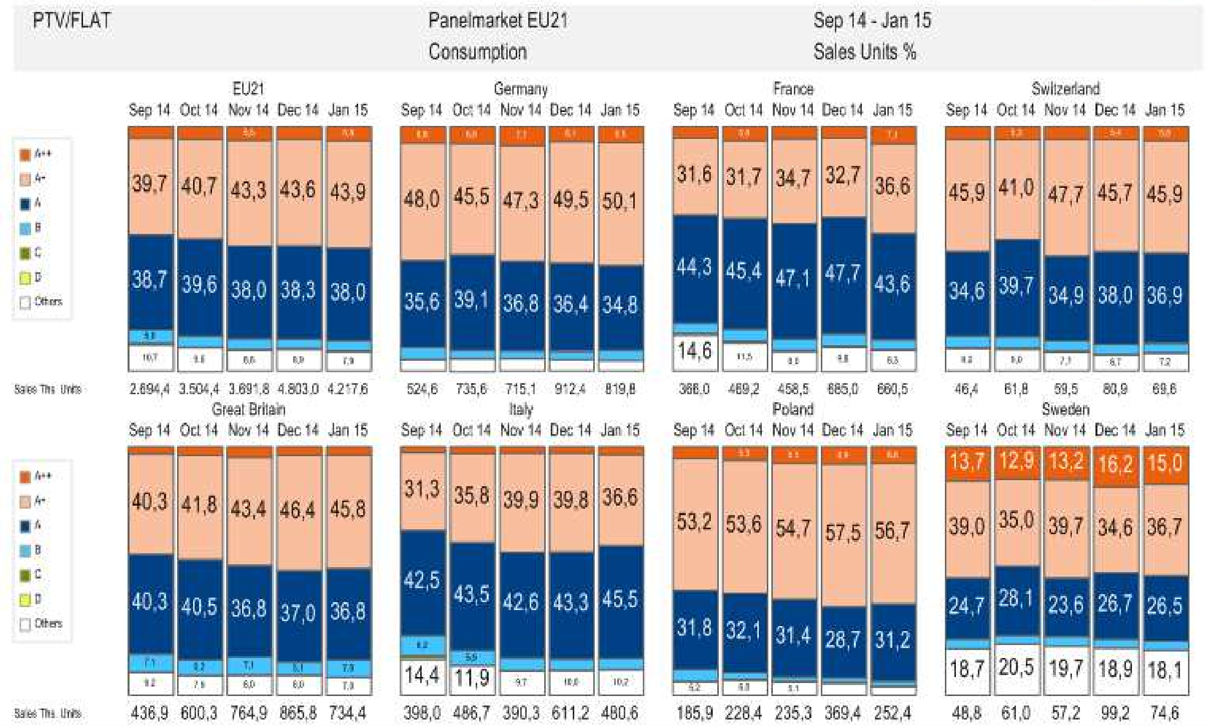


Figure 13: Distribution of the energy label for TV in Europe Jan 15

Summary and conclusions

- The very successful energy labelling of TV in Europe shows that all display technologies are adaptable for energy labelling. The clear communication of energy standards via labels supports consumers and B2B sales in their purchase decision with clear product information on Ecodesign.

- Display and TV technologies are growing together, thus it is important for consumers to have joined energy labelling across product categories. To tap the full benefits and potential of the Ecodesign directive it is necessary to avoid too complex and non-transparent regulations in the implementation and establishing an efficient market control.

- A dynamic and quicker European market monitoring before and after the setting of minimum performance standards would support the Ecodesign directive significantly. A revision of the regulations is needed every 3 years at a minimum.

APPENDIX

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2. Relevant Topic and Related Technology

“Standards and Labels”
“Consumer Electronics”

3. Abstract with Key Words
Page 1

Creating a clear view: setting ecodesign and energy labeling measures for displays

Hans-Paul Siderius, Bob Harrison

Netherlands Enterprise Agency, Intertek

Abstract

Energy consumption of displays (televisions, computer monitors, signage displays) is a significant part of EU electricity consumption: around 75 TWh/year (2,6 %). For historical reasons policy measures for displays are muddled: there are ecodesign and energy labeling measures for televisions, Energy Star for monitors, none for signage displays. Differentiators between displays, e.g. a tuner to characterize a television, that worked well in the past are no longer relevant in the digital area where each display can be fed from a variety of (digital) sources and tuner power requirement is almost negligible. Furthermore, the energy labeling measure for televisions was originally designed for CRT (Cathode Ray Tube) television display technology and does not accommodate very well the specifications of the far more efficient LCD (Liquid Crystal Display) technology, especially with larger screen sizes (above 32 inch). Also improvements in energy efficiency were much faster than foreseen: the energy label class A++ was intended to be populated only from 2017, but by May 2012 the first A++ televisions appeared on the market.

This paper gives an overview on the aspects to be dealt with when setting a measure for all displays, e.g. definition of the scope, dealing with energy relevant features; and identifying stringent test methods.

The paper provides a formula for an energy efficiency index (EEI) that is progressive and can be used for all displays, based on data of almost 1000 televisions and monitors currently on the market. The EEI is the basis for setting energy label classes that provides the end user with a clear view of the energy efficiency of the products in the display market. Also the EEI is used to track the development of the energy efficiency of displays, giving an insight into their future improvement potential.

Introduction

We live in a communication world dominated by visual display products. These are appearing in ever more environments and product applications. Traditional displays like televisions and computer monitors are complemented by smaller displays in products like washing machines refrigerators, coffee machines, photo displays and large displays for advertising. Energy consumption of stand alone displays is a significant part of European Union (EU) electricity consumption: around 75 TWh/year (2,6 %) [1]. Furthermore, in the market the following trends regarding displays can be observed [2]: increasing (average) screen size, increasing resolution, increasing contrast and colour performance and increasing network connectivity. All of these trends would result in the increasing energy consumption of displays. However, on the other side of the balance there are the developments and adoption of more efficient screen luminance and image processing technologies.

Because of the significant energy consumption of products using displays, the trends that increase that consumption and the possibilities for increasing display energy efficiency, policy makers have been interested in adopting measures for displays that stimulate or mandate the uptake of more efficient or less energy using displays. For historical reasons policy measures for displays in the EU are muddled: ecodesign requirements (minimum efficiency performance standards, MEPS) and energy labels for televisions, Energy Star for computer monitors, but none for signage displays. However, the revision of the ecodesign and energy labeling measures occurring at the European Commission (EC) intends to include all displays in the measures. This paper gives an overview of the aspects to be dealt with when setting a measure for all displays, e.g. definition of the scope, the test method and the design of an energy efficiency index (EEI), including dealing with energy relevant features. It is based on input provided to the revision process up to the time of writing this paper (early 2015), notably reference [3].

This paper is organized as follows. In the next section we provide a short overview of the current measures for displays in the EU, including problems with these measures. The third section presents solutions for these problems as part of a proposal for a (revised) measure for displays. It includes a formula for an EEI that is progressive, based on data of almost 1000 televisions and monitors on the EU market. The last section includes discussion, conclusions and recommendations.

Overview and discussion of current measures for displays

Overview of measures; market impact
In the EU currently the following – mandatory and voluntary – measures regarding energy efficiency of displays exist (see table 1).

Table 1 Measures for displays in the EU

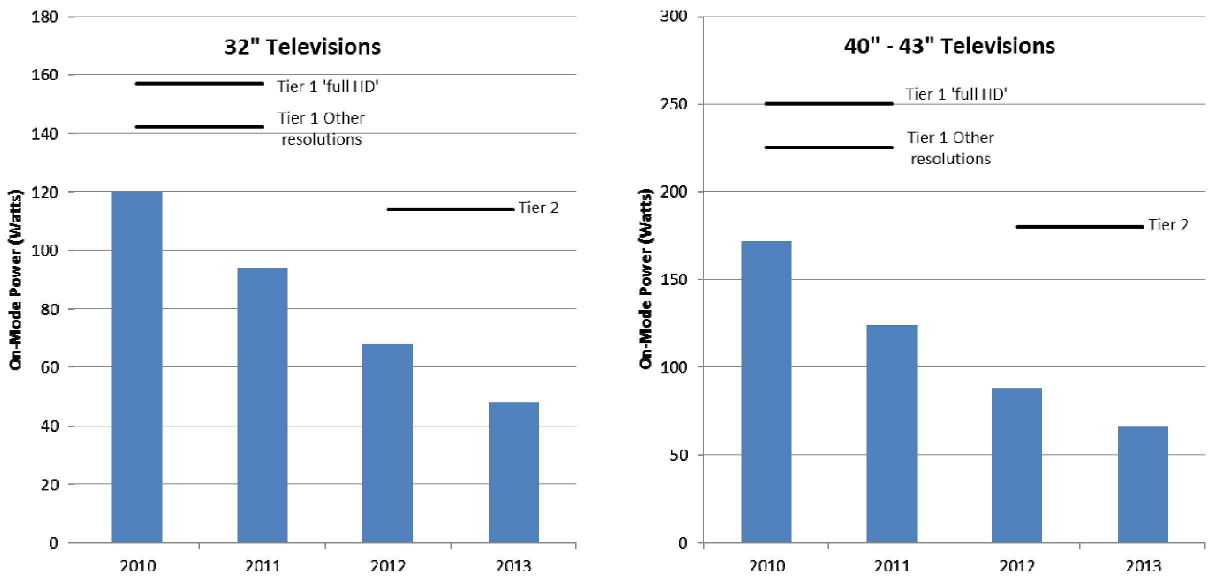
Type of display	Measure	Comments
Television	Regulation 642/2009 (Ecodesign) Regulation 1062/2010 (Energy Label) Decision 300/2009 (Eco-label)	Ecodesign and Energy label are mandatory, Eco-label is voluntary
Television monitor	Regulation 642/2009 (Ecodesign) Regulation 1062/2010 (Energy Label)	Mandatory
Computer monitor	Decision 377/2011 (Eco-label) Decision 202/2014 (Energy Star)	Voluntary

Based on [3], text of the Regulations and Decisions is available at http://eur-lex.europa.eu/en/index.htm

The heart of the ecodesign and energy labeling measures are the formulas that relate screen area with on-mode power consumption. The general format of the formula is:

$$P_{ref(A)} = P_{basic} + \alpha_{screen} \times A \qquad [i]$$

where $P_{ref(A)}$ is the reference on-mode power consumption of a display with screen area A [W]
P_{basic} is the power consumption of the display that is independent of the screen area, e.g. for the tuner, processing or a hard disk [W]
α_{screen} is the coefficient indicating the (inverse of the) screen efficiency [W/dm^2]
A is the viewable screen area [dm^2]



Furthermore, note that the Energy Star requirements for computer monitors includes an additional term that takes into account screen resolution. For the ecodesign measure, the formula provides values for the maximum allowed on-mode power consumption. The energy label classes are based on an EEI that relates the reference power consumption to the measured power consumption: EEI = $P/P_{ref(A)}$.

Figure 1 Average power consumption of televisions sold in EU-24 [3]

In general it is assumed that the ecodesign measures for televisions had little impact on the market: at the time the requirements went into force (Tier 1: August 2010; Tier 2: April 2012) the market average was already significantly more efficient (see figure 1). The explanation is that technology improved much more rapidly than was anticipated when adopting the measure; not only regarding the change from CRT (cathode ray tube) to LCD (liquid crystal display) but also the change from CCFL (cold cathode fluorescent lamp) to LED (light emitting diode) backlighting and the efficiency improvements in LED backlighting.

Figure 2 shows the rapid uptake of televisions in the highest energy labeling classes. Energy labels with A++ as highest class were planned to be introduced in 2017, however A++ televisions already appeared on the market almost 5 years before (April 2012).

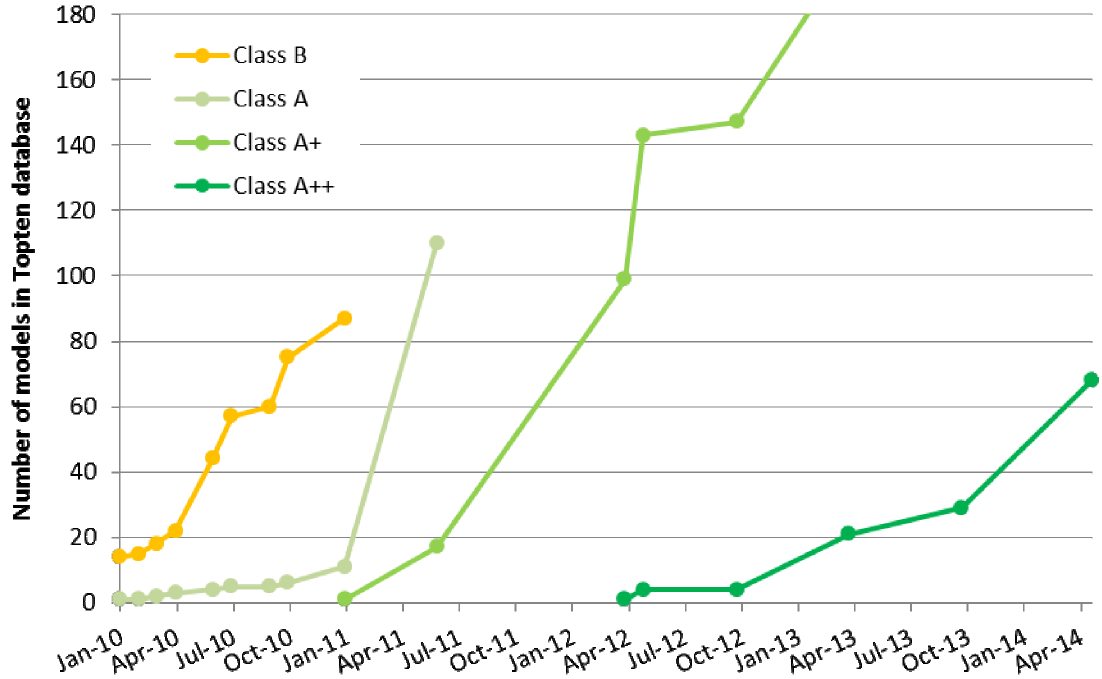


Figure 2 Number of televisions in highest energy label classes [4]

Figure 3 shows the development of the average EEI over time. The formula for the trend line is:

$$EEI = 1.0707 \times e^{-0.221(\text{year}-2007)} \quad \text{[ii]}$$

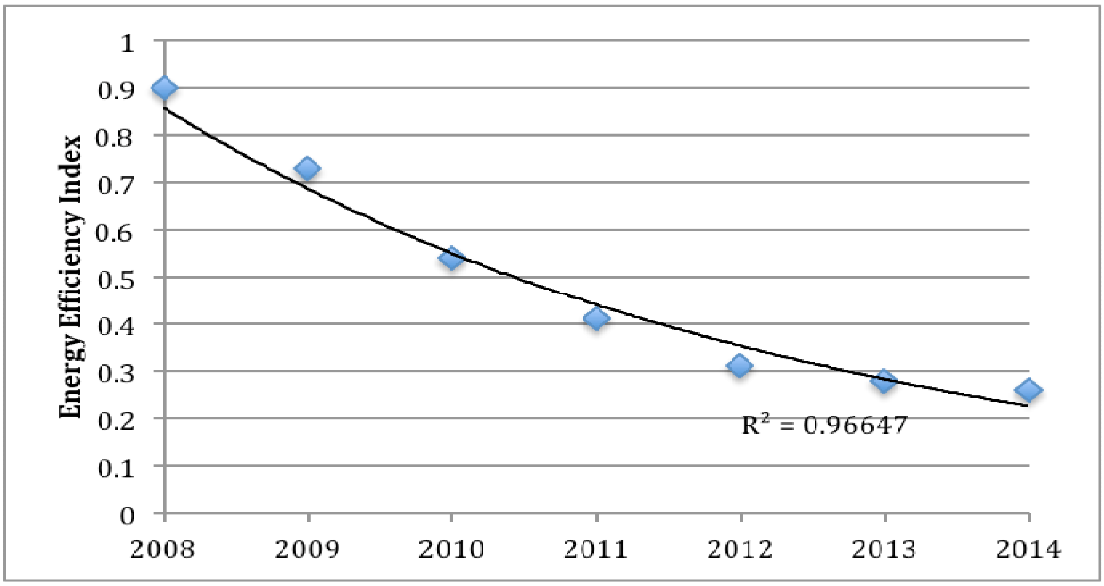


Figure 3 Development of EEI; [5] with data for 2013 and 2014 added

Discussion of problems: lessons to be learned
From the overview in the foregoing section we select the following critical issues regarding measures for displays: the scope of the measure (product definition), the design of the formula, the setting of minimum efficiency requirements and labeling classes.

Scope of the measure (product definition)
The assumption behind having different measures for different types of displays is that product definitions can differentiate in an unequivocal manner. The product differentiation between a television and a television monitor in ecodesign and energy labeling measures relied on different input signals and the presence of a tuner for televisions. Nowadays many displays are designed to accept a variety of (digital) input signals, including broadcast signals for which a tuner is required. Also, the importance of the tuner-receiver regarding energy consumption has decreased dramatically, a factor of 10 since 2009. Moreover, since ever more content is distributed via the internet, the importance of a tuner as such has decreased. In general it has become increasingly difficult to distinguish between types of displays (or applications) on pure technical characteristics without running the risk of creating loopholes in the regulation[1].
Another issue regarding the scope, is the border with computers. On one hand, computers with integrated screen and large (signage) displays that contain a server and data storage exist on the market, on the other hand televisions can have very powerful processing capabilities, run third party software (e.g. apps) and accept input through an external keyboard.

The design of the formula (allowances)
The original formula in Regulation 642/2009 [7] was largely based on CRT data. Current market data shows that a linear formula is not providing the best fit, especially when using one formula for small and large displays: a linear formula that fits small displays is too "generous" for large displays and vice versa. This is explained by three factors,

- Where a high performance display (e.g. high definition (HD) and ultra-HD (UHD) or 3D) is considered, the input signal and screen drive processor power is the same for a large or small display.
- Expensive manufacturer innovations in efficient processing and related data storage for input signal and screen drive processing are first applied to high end products which are invariably large screen products in the domestic sector.
- Step changes in display technology which involve expensive manufacturing through poor yield or heavy initial production line investment (e.g. direct backlight for UHD displays with quantum dot (QD) nanocrystal filter) will be aimed initially at the large display high-end market for maximum cost recovery and controlled trouble-shooting of a low volume output.

Another aspect of the formula is whether, how to and if to, take into account energy relevant features, e.g. resolution, network capability, hard disk, 3D. Regarding resolution and 3D, the impact is both on the power consumption for the screen (higher luminance requirement) and for the processing. The issue with allowances is twofold. First, the decision as to which features allowances are to be set, and second how large the allowances should be. In most cases the data available for deciding on the (level of) allowances is the data of the products available when preparing the measure. Unfortunately, this gives little insight into the further development of energy efficiency of the features, nor regarding the development, and the energy consequences, of new features. The experience with the television regulations for ecodesign and energy labelling shows (figure 1) that the allowances for full HD (High Definition), multiple tuners and hard disks were too generous in light of the development of energy efficiency of these features. The average standby power consumption of hard disks in 2013 is 2.2 W [6], whereas the allowance in the energy label formula is 4 W. Nowadays tuners providing two digital, terrestrial and satellite data streams have a typical power consumption of 0.5 W, whereas the allowance is 4 W. On the other hand this provided room for features for which no allowances were provided such as higher display luminance levels, advanced signal input interfaces (HDMI). 3D is an example of a feature of which the success and therefore the further uptake is questionable [3]; main

[1] Note that especially mandatory regulations need definitions without loopholes, contrary to voluntary schemes like Energy Star or an ecolabel where the manufacturer is intrinsically motivated to meet the product definition.

reasons seem to be the lack of 3D content and the discomfort of wearing (polarized/switched) glasses. Network capability is not an issue that is unique for televisions, but it can have some secondary consequences because internet content, at least until recently, had a higher average picture level (APL) than standard broadcast images and could trigger the use of wider screens for picture-in-picture viewing [2].

Setting of MEPS and labeling classes
Setting the right MEPS level and labeling classes is difficult for electronic products. Life cycle calculations do not provide guidance since no correlation exists between energy efficiency and the product price [5]. Forecasting efficiency developments of key components, e.g. processors, memory, backlighting and panels could provide help, but this information is often difficult to get. Moreover, information on new features is even more unlikely to be publicly available.

In the next section we show how these aspects can be dealt with in (revised) measures for displays, including the test methods needed.

Setting a measure for displays

Product definition
In principle the product definition for a display can be simple: 'Electronic display' means a product with a display screen and associated electronics of which the primary function is to display visual information. However, such a comprehensive definition requires attention for special displays, e.g. very small or very large, or designed for a special use such as medical or studio applications. Very small displays, e.g. displays with a screen area of 5 dm^2 or less, are probably status and/or control displays built into products with a primary function other than that of displaying visual information . Although from an energy efficiency point of view, there is no reason why the display part should not be as efficient as dedicated display products, there are some practical issues with "double" regulation, i.e. situations where both the product and one or more parts are regulated. Therefore it is advised to use a minimum screen area. Products with very large screens, e.g. a screen area of 1000 dm^2 or more, are probably custom ordered or made up of series of smaller screens. This means that also an upper limit on the screen area of the product is useful.

The design of the formula
The formula for the maximum (ecodesign requirement) or reference (EEI for energy labeling) power consumption value is based on the formula concept in the Energy Star version 7.0 draft for televisions but calibrated on the dataset of EU 2014 models. The Energy Star formula of power versus screen area is non-linear, i.e. it gets flatter for larger screen areas, or said otherwise: the power requirements per unit of screen area become more stringent for larger televsions. The EU dataset comprised almost 1000 models including PC monitors. The display technology was limited to LED backlight LCD which totally dominated the market. Plasma display and CCFL backlight LCD display products were clearly identified by the manufacturing industry as dead technologies for future EU domestic products and the related data was not allowed to distort the database analysis. Signage displays were also eliminated from the database analysis because of their wide range of display luminance and their energy intensive additional functionalities. The formula derived as an optimum from the database analysis provides a curve that is almost linear for smaller[2] screen areas and flattens for larger screen areas.

$$P_{max} = \alpha_1 \times [\alpha_2 \times \tanh(\alpha_3 + \alpha_4 \times (A-\alpha_5)) + \alpha_6] + \alpha_7 \qquad \text{[iii]}$$

Or in the format of the current formula: $P_{max} = P_{basic} + f(A)$, with $P_{basic} = \alpha_7$ and f(A) the tanh formula; this means that the linear part α_{screen}xA has been replaced by the non-linear tanh formula. Although in principle all parameters α_1 to α_7 can be varied to accommodate the requirement for different Tiers or labeling class boundaries, for clarity and simplicity it is recommended to use an EEI (see next section). Note that formula [ii] does not include resolution or any other feature, e.g. better colour reproduction. This decision was based on the dramatic and ongoing improvement in the energy efficiency of the data processing for input signal conversion to display drive and in the LED backlight efficiency. Early (2014) testing of the more advanced ultra-HD (4K) resolution display products giving

[2] Note that the smaller screen area is the range covered in the past by CRT displays.

extended colour performance endorsed the decision. It is further endorsed by 2015 declared manufacturers data for UHD televisions distributed in the European market (table 2).

Table 2 UHD (4K) televisions pass rate proposed EEI Tier 1

Screen Area	Number of UHD TV (4K) distinct models in 2015	Pass percentage for proposed Tier 1 EEI of Revised Displays Regulation (expected 2017)	Pass Percentage for existing 2012 Regulation EEI
All screen areas	116	67%	100%
From 10 to 25 dm²	0	NA	NA
From 25 to 50 dm²	17	88%	100%
From 50 to 75 dm²	24	75%	100%
From 75 to 100 dm²	40	75%	100%
From 100 to 150 dm²	22	59%	100%
150 dm² and above	13	38%	100%

Measurement method
It is important that the measurement methodology for the key data input supporting the product compliance with MEPS and labelling sets testing conditions close to the "real life" usage of the product and has good resilience to "gaming" (the ability of the product to recognise a testing sequence and automatically modify performance parameters to assist compliance). The methodology should ideally allow also, a flexibility of testing conditions to give Market Surveillance Authorities an easy low cost initial assessment of product regulation compliance outside the test laboratory. For display products the following aspects are specifically relevant:

- The status of auxiliary functions, including sound;
- Display settings for measuring power consumption, especially luminance.

The European and international standard EN/IEC 62087 Edition 3.0 is currently accepted as the reference standard for the measurement methodology for the, on-mode, low power modes and off-mode testing of display products. This standard indicates that auxiliary functions that can be switched off by the user, should be switched off for the power measurement in on-mode. Manufacturers who do not provide power management for auxiliary functions (e.g. internal media players) clearly understand that the power requirement of these functions will impact adversely on the potential compliance with ecodesign requirements and labelling level of the display product.
Measurement of the sound reproduction efficiency of any product that combines sound power amplifiers and loudspeakers is a very complex process. The Standards working groups that considered display product power measurements took the pragmatic decision that because the sound part of a display product universally used identical power amplifier characteristics (negligible power requirement at low audio levels) the simplest testing condition for the sound would be a "just audible" setting". This has proved to be an acceptable rationalization of dealing with the complexities of sound power measurement and the problems of approximating the range of sound programme content for measurement purposes. For the future where digital broadcasting standards may include complex sound processing (e.g. up to 24 channels of sound) it may be advantageous, in the context of assessing the MEPS of a display product, to have a special testing on-mode that disables the power to the sound circuitry.

Regarding the settings, the choice is to measure at fixed, i.e. the same for every display, settings, e.g. a luminance level of 200 cd/m^2, or to measure at the settings as delivered by the manufacturer ("out of the box"). In case of out-of-the-box settings a minimum requirement for the luminance ratio ($L_{out-of-the-box}/L_{max}$) is needed, because otherwise manufacturers could ship products with low luminance levels in order to meet the minimum efficiency requirements or a certain energy label class while such a low level would never be used in practice. In the current ecodesign regulation a minimum luminance ratio of 65 % is required. The measurement of the ratio is more simple and reproducible than the measurement of an absolute luminance value.
The pragmatic approach of using the delivered (out-of-the–box) settings for display product compliance testing has proved reliable for domestic and office products but is not appropriate for

specialist displays such as those for public signage. These displays can have brightness levels of over 3000 cd/m^2 (compared with 300 to 400 cd/m^2 for domestic products) and often incorporate servers and network control functions all using a common power supply. A completely different set of compliance criteria will be required for them.
A common feature of current display products is the Automatic Brightness Control (ABC) This function modulates the peak luminance of the display to optimize the viewing experience at the lighting level of the viewing room (e.g. from bright sunlight to mood lighting at night). This feature has the potential to reduce the power requirement of the display by up to 80% of the out-of- the- box setting[3]. However there are no standards in place for the control characteristics of the ABC function and a rather simplistic approach is used to set compliance requirements in the EU labeling regulation. The currently suggested testing methodology for ABC compliance is time consuming and needs to be addressed urgently for future regulation support especially in the context of efficiently plotting the control characteristic of the ABC system over many illuminance points.

Setting of MEPS and labeling classes
As indicated in the discussion of current measures, the setting of MEPS and to a lesser extent energy label classes, is difficult because it needs to take into account developments of (energy efficiency of) technology. We distinguish between:

- old technology, e.g. PDP (plasma display panel);
- new technology (not yet on the market or in early stage of production), e.g. OLED (organic LED) or QLED (quantum dot LED);
- future development in features, e.g. resolution, color reproduction, high dynamic range luminance.

Especially for ecodesign requirements that regulate market entrance, care need to be taken not to significantly restrict product choice or development. On the other hand, policy makers do not want to keep inefficient technologies on the market for which a more efficient alternative exists. Also, it is reasonable to ask manufacturers who develop new product features and functions that these new products are not (significantly) less efficient than existing products, especially when it is known that trends in major components point towards more efficiency and that these new products can in principle be made as efficient.

Regarding the aspects mentioned above, we argue that there is no need for an exemption for PDP displays because they have no longer exceptional features that other technologies have not. Quantum dot (QLED) technology is more efficient than current LED backlighting but part of this improved efficiency will be used to achieve a brighter picture (higher luminance). Allowances for features such as full HD and multiple tuners were based on the assumption that these features require more processing power. However due to improvements in silicon and processor architecture, these features can now be implemented with little or no overhead. Because of the problems with allowances as indicated above, we do not include allowances in the formula for the maximum power consumption.

We propose to use a combination of MEPS and energy labels, where the MEPS are not too stringent to allow for new technologies and features, and the (highest) energy label classes are set at a very ambitious level to recognize the most efficient products (in the near future), regardless of features and new technologies. So a display with a high resolution that is less efficient could still be placed on the EU market, but would probably have an energy class E (one class below average). The following proposal is based on this reasoning.

The proposed formula for the EEI is:

$$EEI = P/P_{ref(A)} \qquad [iv]$$

$$\text{with } P_{ref(A)} = 3 \times [100 \times \tanh(0.02 + 0.006 \times (A-11)) + 4] + 6 \qquad [v]$$

[3] See http://www.energystar.gov/products/spec/televisions_specification_version_7_0_pd, section "Draft 2 Version 7.0 Specification: Draft 2 V7_TVs_EPADataset_0" xls Sheet "Data" and compare on-mode power home – mode as delivered and 3 Lux ABC (xls columns L and V).

Figure 4 shows the $P_{ref(A)}$ curve for screen areas between 10 and 450 dm^2, clearly illustrating the flattening of P_{ref} for screen areas larger than around 300 dm^2 (around 2,6 m diagonal in wide screen format).

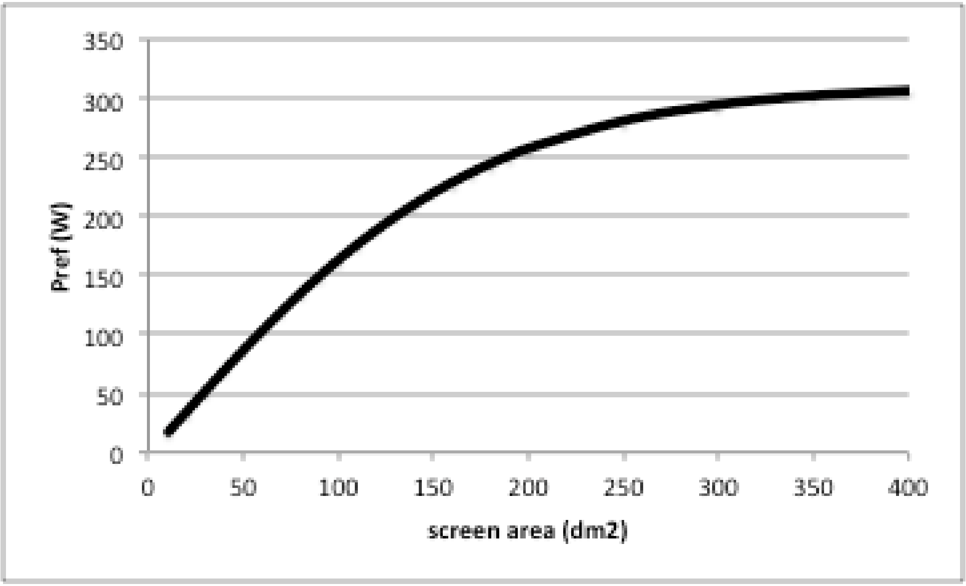


Figure 4 **$P_{ref(A)}$ curve**

Table 3 provides the energy label class boundaries and proposals for two Tiers for ecodesign minimum efficiency requirements. The Tiers could enter into force one year (Tier 1) and three years (Tier 2) after the adoption of the regulation. Since as explained in the discussion on the formula, there is a technological reason to move away from a linear curve to a non-linear curve, it does not make sense to keep the old formula for the energy label. On the contrary, the new formula can also be used to rescale the energy label classes for televisions in order to get rid of the “plus” classes (A+, A++ and A+++); see the evaluation of the energy label for an extensive discussion on this subject [8].

Table 3 Energy label class boundaries and ecodesign minimum efficiency requirements

Energy label class	EEI	Minimum efficiency requirements
A	< 0.17	
B	< 0.33	
C	< 0.50	
D	< 0.66	Tier 2: EEI < 0.66
E	< 0.83	
F	< 1.00	Tier 1: EEI < 1.00
G		

Table 4 shows the distribution of 2014 models over the proposed energy label classes.

Table 4 **Distribution of 2014 models over proposed energy label classes**

EEI	1.00	0.83	0.66	0.50	0.33	0.17	
	G	F	E	D	C	B	A
All (n=980)	266	115	226	247	118	8	0
	27%	12%	23%	25%	12%	1%	0%
UHD (n=43)	20	6	13	4	0	0	0
	47%	14%	30%	9%	0%	0%	0%

Table 4 shows that 73 % of the 2014 models would meet Tier 1 and 38 % would meet Tier 2. For UHD televisions this is 53 % and 9 %.
The energy savings of these proposals can be estimated as follows. If all 2014 models in class G to C would improve 1 class, this would result in 24 % energy savings. Assuming that displays with class G would become class F, Tier 1 results in 8 % energy savings, and assuming that displays in class F and E would become class D, Tier 2 would result in 7 % energy savings. Note however that the savings from the energy label and the ecodesign measure are not cumulative.

Discussion, conclusions and recommendations

Discussion: keeping track of technology development
From the discussion of the current measures and the setting of a revised measure for displays we select two general discussion points: the development of technology and the (autonomous) development of energy efficiency of displays. As shown in the foregoing sections, development of technology impacts all aspects of a measure for displays: the product definition, the design of the formula, including allowances, and the setting of requirements. In our proposals we have tried to avoid forecasting of technology developments to set requirements or to establish a formula for the on-mode power consumption of displays. There is a practical and a fundamental reason for this position. The practical reason is to avoid long discussions that are biased because of information asymmetry between manufacturers and policy makers. More fundamental is the opinion that in any case ecodesign and energy labeling are *product* policy measures and not (primarily) technology development measures. Nevertheless, information on future developments can be useful, certainly regarding general trends in efficiency developments for components. However, we argue that this can not be the sole basis for product efficiency policy measures for displays.

The development of technology also influences the (autonomous) development of efficiency. Siderius [5] argues that policy makers should be cautious in setting MEPS for products that have a PAW (policy action window) of less than 3 years, because in that case the autonomous development in efficiency will probably be faster than the policy making process. He calculates a PAW of 2.2 years for televisions. And indeed – as we indicated – the efficiency of televisions shows a rapid development. However, also this recommendation is made under the assumption that the technology underlying the efficiency improvement is “stable” or at least predictable. In this paper we have shown that this assumption – at least partially – does not hold for displays. Thus, MEPS and energy labels are used as “sign posts” to guide the energy efficiency of displays when technology changes and/or new features are adopted.

Conclusions and recommendations
In this paper we have shown it is possible to set energy efficiency measures (MEPS, energy label) for a large range of displays (televisions, computer monitors, non-specialist signage displays) without having to care about the type of display. The proposed formula acknowledges that the efficiency of displays increases as the screen area increases.
The energy savings range from around 7 to 8 % (each Tier of the ecodesign measure) to 24 % (energy label), noting that the savings from energy labels and ecodesign are not cumulative.

The development of technology plays a large role in the development of energy efficiency of displays. On one hand displays become more efficient, e.g. through improved efficiency of LED backlighting and more efficient processors. On the other hand, some of this improvement is used for new features, e.g. higher resolution or better color reproduction. Therefore the combination of MEPS and an energy label is useful for displays. MEPS that restrict the entrance to the market should not be too stringent and allow room for new features, whereas energy label classes should be set at an ambitious level to stimulate the uptake of low power consumption displays, even for those with many features. Experience with HD and tuners shows that the extra power needed for new features is absorbed by technology improvements in the next generation – when the features are no longer new. This means there will be room again for new features. Thus, setting not too stringent MEPS preempts the need to define and set allowances for individual features.

Specialist signage displays - very large (> 1000 dm^2) displays or displays with brightness levels of over 3000 cd/m^2 and incorporated servers and network control functions - are not covered by the proposed approach because they need a different measurement method and criteria that acknowledge the high brightness level and server capabilities. It is recommended to develop this measurement method and criteria on short notice since the number, and thus the energy consumption, of these displays is increasing.

Since displays are world wide traded products, it is recommended to harmonize test methods and efficiency measures for displays world wide. This does not mean that the efficiency requirements and energy label classes need to be same, but they could be based on the same formula or EEI.

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Technical considerations in achieving greater international alignment in television test methods and performance requirements

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Abstract

This paper reviews the technical considerations involved in working toward global harmonisation of television test standards and energy efficiency policy.

First, the potential to harmonise test methodologies for televisions is assessed. Various improvements to international and regional test methodologies are suggested that would facilitate global harmonisation.

The second part of this paper takes a policy perspective, presenting results of an analysis of national television performance standard and labelling policies. Findings highlight a startling array of different labelling and minimum energy performance standard (MEPS) thresholds in use around the world, despite televisions in different regions being technologically very similar. Policy stringency is assessed against an aggregate data set of over 10,000 televisions that is representative of the US and Australian markets of 2011 to 2014. Ambition in many labels and performance standards was found to be lacking, with data showing ample scope for governments to tighten standards whilst retaining a wide consumer choice.

Based upon this analysis, the paper proposes a methodology to facilitate the development of internationally-comparable and aligned representative efficiency thresholds that are ambitious but easily implemented. The methodology is based on a series of benchmark performance levels that policy-makers can use for setting local policies and labelling schemes.

Finally, this paper discusses how implementation of its recommendations could be catalysed by policy-maker involvement, and facilitated through a range of international collaboration opportunities arising from initiatives such as the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative.

Introduction

Global television sales continue to grow, particularly in major domestic markets such as China and Africa. Sales are spurred on by the continuing fall in product prices. The selling price per TV fell by 43% between 2008 and 2011 [1]. At the same time, televisions currently account for an estimated 3% to 8% of global residential energy use [2]. Considering the global nature of the television supply chain and potential environmental impacts of continued growth in the sector, it is important that a level playing field is established internationally in terms of testing methods and performance requirements relating to energy efficiency.

This paper analyses current energy efficiency performance standards and test methods for televisions in order to develop proposals for internationally harmonised energy efficiency test methods, metrics and efficiency classes for use in future efficiency policy measures.

The work presented in this paper was supported by the Australian Government and CLASP, in partnership with the Asia Pacific Economic Cooperation Expert Group on Energy Efficiency and Conservation (APEC EGEE&C), SEAD, and the APEC Collaborative Assessment of Standards and Testing Methods (CAST) program. The work was undertaken by Intertek PLC, Tait Consulting, Digital CEnergy Australia and Topten Europe.

There is a particular focus in the analysis on APEC countries that participate in SEAD, and certain other relevant economies (including but not limited to Australia, China, India, Japan, Korea, the Philippines, the United States, and Vietnam, plus, although not part of APEC, the European Union).

APEC governments have endorsed this work, as they are keen to work toward a globally harmonised standard that will support eventual aligned efficiency tiers/MEPS/labels.

Potential to harmonise test methodologies for televisions

Whilst six television test methods were identified in use in the countries addressed in this analysis behind this paper, they all rely on the test methodology of the dynamic broadcast-content video signal for the basic on-mode power measurement that is the foundation of IEC 62087, including Japan and China. However, challenges in the detail of test methods remain – in particular due to the differences between the following two standards:

- IEC 62087: This addresses on mode testing of TVs, and is usually partly referenced (with regional variations) or directly adopted by most existing international test standards (see Figure 1). A major rewrite is in the process of being finalised in 2015. The numbering will change from "IEC 62087 Ed. 3.0" to address TVs in the following parts: IEC 62087-1 Ed. 1 (General), IEC 62087-2 Ed.1 (Signals and media) and IEC 62087-3 Ed.1 (Television sets). The findings of this paper are relevant to a subsequent revision.

- GB 24850-2013: This is the testing method used in China, and is different to IEC 62087 in terms of sample preparation pre-testing. The test method also prescribes policy requirements, which are based on a luminance (candelas per Watt) metric, rather than an efficiency metric (watts per unit area of screen size) as used in other regions.

These two are therefore the key standards relevant to international harmonisation efforts.

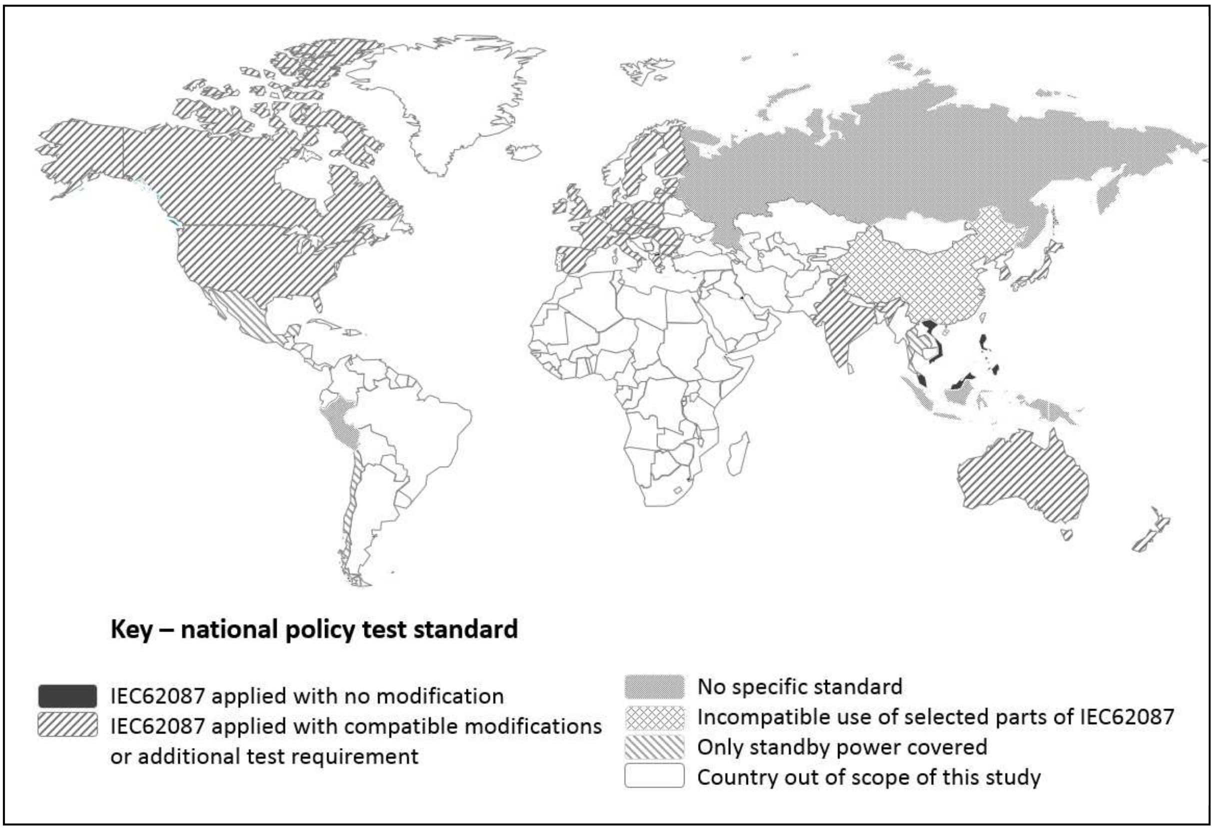

Figure 1. World map showing IEC 62087 harmonisation. Comparison assumes that policies are based upon IEC 62087 edition 2 or edition 3, which are reasonably comparable for energy measurement [4].

APEC countries without standards, where work could be done to improve engagement on TV–related energy efficiency initiatives include Brunei Darussalam, Indonesia, Papua New Guinea and Peru.

Key findings on test method comparison

Reasons for variations in the application of test methods include the evidence locally available to policy-makers, timing of transition to digital TV broadcasting - and differing consumer attitudes toward default product settings. Laboratory set up between countries is relatively consistent and not considered a cause for differences (variation lab-by-lab has been shown in recent studies as down to training and misinterpretation of standards rather than any justified local realities). Key observations include:

Test methods need to evolve alongside TV technology: To keep pace with TV technology development and ensure that test results reflect actual in-home energy consumption, continued updating of test methods is necessary. For example, to account for increasingly sophisticated picture optimisation algorithms, automatic brightness control (ABC) functionality and new broadcast formats such as ultra high definition (UHD) and 3D.

Some harmonisation progress has already been made: There is a good alignment on: measuring equipment requirements; the broadcast content test video signal; and confidence level requirements for measurement of uncertainty. The extent of global harmonisation with the IEC 62087 standard is shown in Figure 1. Some regional variations are a necessity e.g. different ambient temperature ranges or input voltages, which may have a small impact when comparing test results between regions.

Sample preparation is a key concern: TV sample preparation prior to testing has the greatest impact on comparability of energy test results. The sample preparation for GB 24850-2013 requires the subjective luminance and contrast configuration of a grey-scale test pattern. This is influenced by the perception of the individual setting up the test and adds an unquantifiable variability to testing results. Regions using IEC 62087 usually test televisions as supplied from the manufacturer, in the configuration as supplied 'out of the box', resulting in more consistent testing results between laboratories. This provides a good indication of the energy impact of the product in "real life" use. Compensation for some differences in test methods can be made by normalisation approaches to make test results more comparable after the test, by adjusting energy results using calculated or empirical factors. However these are unlikely to be sufficiently robust to enable fair comparison of the results of tests carried out in many international regions (using IEC 62087) with tests carried out in China (using GB 24850-2013).

Policy requirements add to testing divergence: Policy approaches can introduce additional variance in the application of testing approaches in some countries. Key areas for harmonisation in policy relating to testing approaches include i) standardisation on the illuminance levels used for ABC testing (i.e., the light shone onto the television to stimulate ABC), ii) incentives for use of ABC, and iii) harmonised approaches to peak luminance levels in policy.

Priorities for harmonisation of test methods

Figure 2 shows the high, medium and low priority issues identified for harmonisation of testing. High priorities have the biggest impact on the comparability of test results.

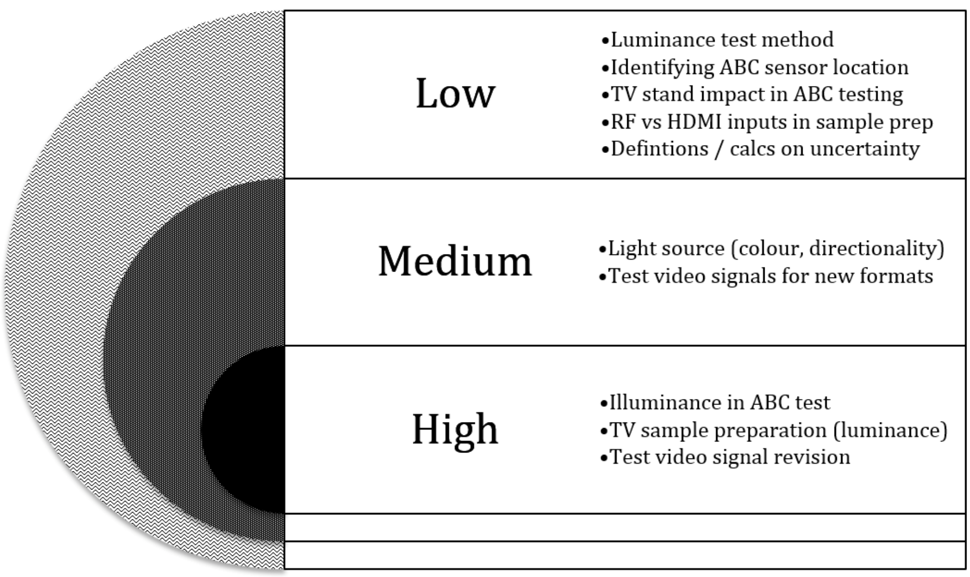

Figure 2. Priorities for TV testing harmonisation

Apart from sample preparation which has already been discussed, there may be a need to revise the input signal (the "dynamic broadcast-content video signal") so that it provides representative results for new televisions. For all TVs tested in the laboratory that had intelligent (dimming) screen drive, the IEC broadcast content video signal (containing short cuts of different footage) gave consistently lower average on-mode power results than an alternative single-source test signal [4]. As a result of this issue, measured TV power demand may be currently understated by around 10% compared with viewing more typically done in the home. This necessity for change is unfortunate as the broadcast-content video signal is currently well harmonised. A change in the test video signal would have to be carefully managed, particularly as once testing shifts to a new signal, results will no longer be comparable with the old video signal. Where the TV declared power is used as a basis for regulatory or labelling conformance it will be important to minimise market disruption by synchronising changes in regulations and labelling specifications across participating countries (notably for ENERGY STAR, EU and Australia). However radical proposed changes in future video formats such as High Dynamic Range (HDR) TV and Dolby-Vision TV will be the catalyst for a new test video signal.

There is another primary weakness in all the current test standards regarding the need to set, test and declare screen luminance and ambient light levels (illuminance) in some way, as this is prone to errors. This is particularly an issue in the following areas:

- Application of the Chinese test standard due to configuration of screen luminance prior to testing (as previously discussed).
- Measurement of ambient light levels for ABC testing at different levels, as this can require a mechanically complex test rig to guarantee very precise positioning of the light source for consistent results.
- Measurement of out of the box luminance level in order to compare it with the peak luminance level and clarify that the results are within the range prescribed by policy (to avoid manufacturers setting default luminance unreasonably low, for more favourable energy test results).

There is also a need for consistency in the specified illuminance levels and calculations specified for on mode testing with automatic brightness control (ABC).

Towards closer harmonisation of test methods

One of the most beneficial developments in the test standards area would be the refinement of testing light sources, which (accompanied by appropriate test material) could allow for more robust setting of illuminance in ABC testing and reduce the severity of many of the other testing issues identified.

Above all, greater harmonisation of test methodologies between Chinese and IEC approaches (principally in terms of the approach taken toward screen luminance in sample preparation) is essential. There is no sufficiently robust current method to translate the results of individual tests between the two test approaches to allow comparison between China and other regions.

In practical terms, the opportunity to change or adjust existing test methods is constrained by a number of factors including those shown in Figure 3.

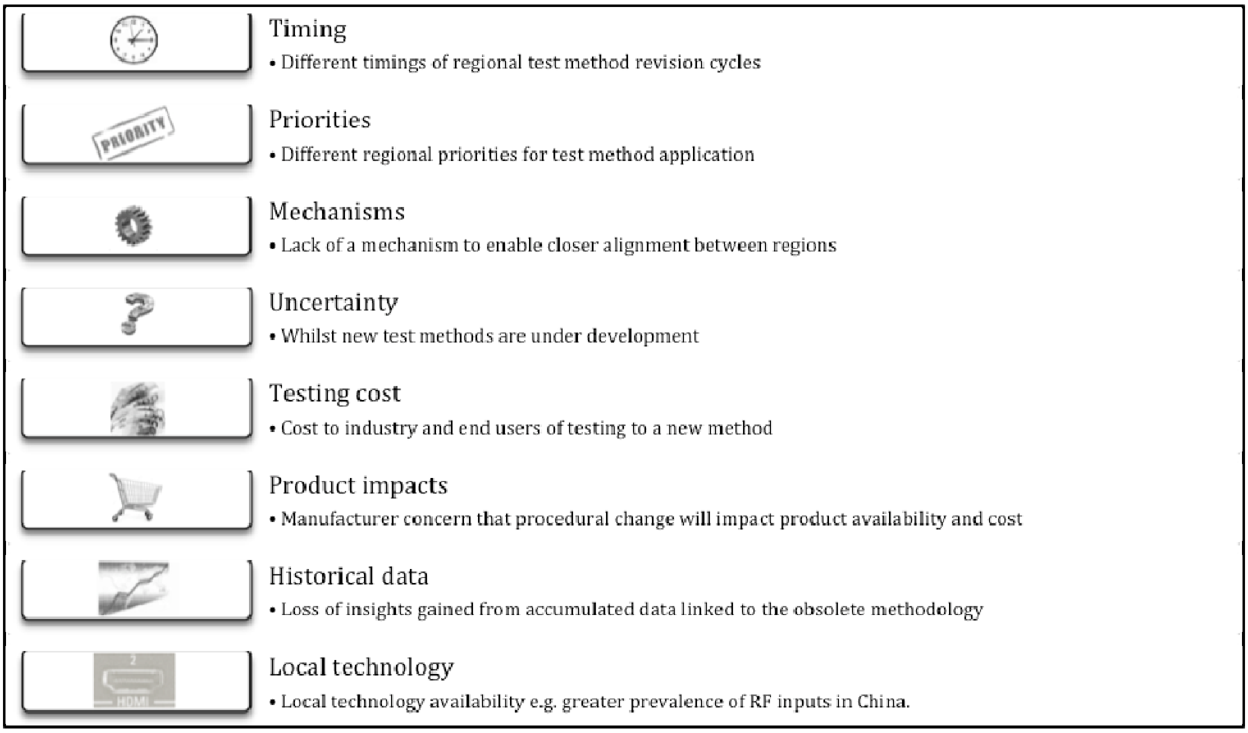

Figure 3. Barriers to change of test methods

Potential to harmonise television performance thresholds and labelling policies

Analysis of policies in 13 regions revealed a startling array of over 70 performance thresholds in use. Only a handful of these coincided, despite televisions using very similar technology the world over. These include: Australia (10 levels); China (3 covering two technologies (LCD and Plasma)); EU (9 labels plus 2 MEPS); Hong Kong (4); India (20, by screen technology); Japan; Malaysia (5); Republic of Korea (5); Singapore (4); Taiwan; USA (California and ENERGY STAR); Vietnam (5).

Different policy approaches

Most television efficiency policy metrics use a formula to calculate an allowable on mode power demand, based upon the screen area (calculated in Watts per unit screen area). However, alternative approaches were identified such as the Malaysian efficiency metric based upon annual energy consumption (AEC) that takes into account the passive standby power and in some cases the active standby power; and the Korean metric which is based on screen dimensions. The Chinese metric is based upon screen brightness (in candelas) per Watt. Previous research has shown that this approach can favour brighter, rather than more energy efficient TVs [6].

As mentioned earlier, policy approaches can also introduce additional variations to test methods in some countries by specifying additional requirements. Priorities for harmonisation in policy relating to testing approaches include:

- Standardise the illuminance levels specified for ABC testing,
- Standardise the allowances in calculations for ABC on mode - This can be a weighted calculation based on testing results at different illuminance levels or a fixed allowance for the presence of the technology if it achieves a minimum reduction in power demand at a specified illuminance.
- Standardise luminance ratios in policy where products are tested with samples in ‘out of the box’ status - testing of out-of-the-box luminance level can be required in some policies in order to establish the ratio between peak and out of the box luminance. By imposing a

minimum ratio for this (first initiated in Australia, and since in the EU and US), manufacturers are prevented from ‘gaming’ the policy through configuring factory default settings too dim for use in homes in order to achieve better test results.

Policy requirements cover minimum energy performance standards (MEPS) that regulate to prevent the worst performing products being sold on a market, and energy labels that influence consumer purchasing decisions toward higher energy efficiency. Energy labels can also provide a clear policy path for MEPS over time, through elimination of lower labelling classes.

Different countries take different approaches to metrics for efficiency. Figure 4 summarises the main approaches for metrics identified in the analysis supporting this paper.

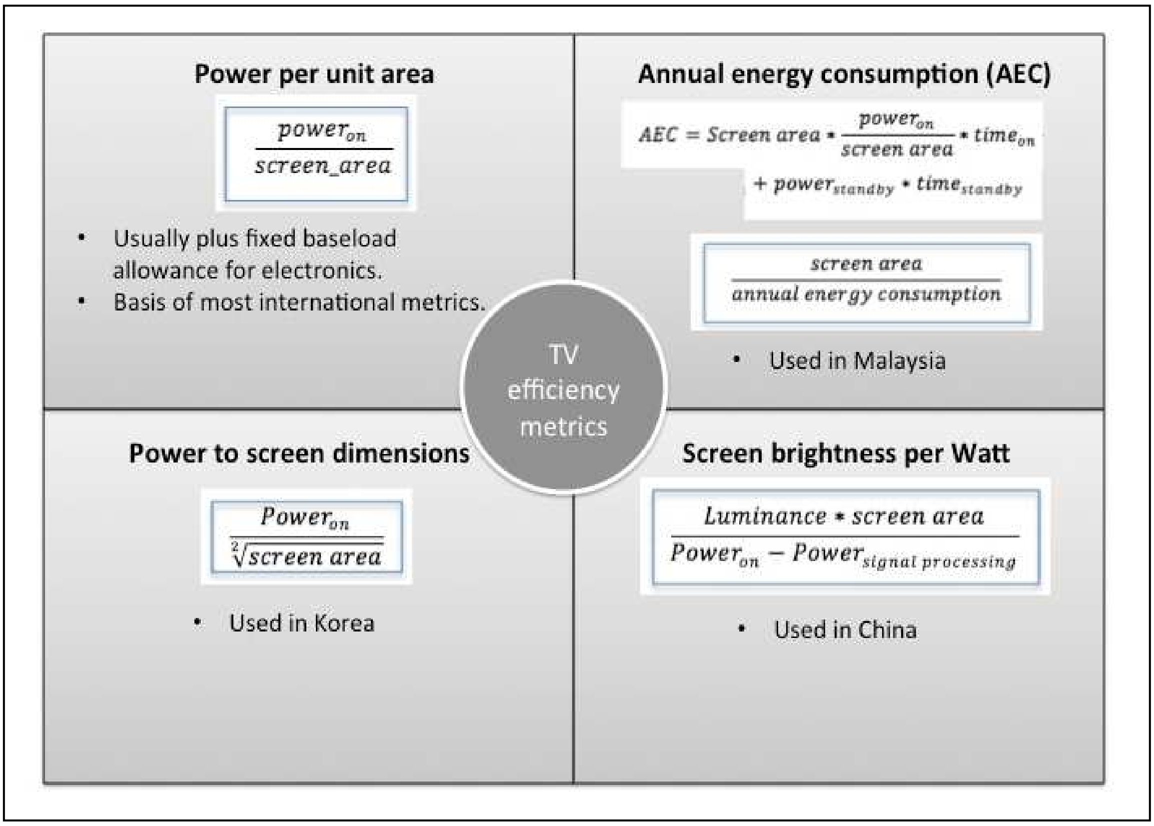

Figure 4. The four main approaches to defining TV efficiency metrics in the regions studied.

In addition to the above approaches, there is also the Top Runner approach used in Japan – where mandatory energy efficiency standards are set based on the most efficient (“top runner”) products on the market. Products are assigned to categories on the basis of their features (e.g. screen size, screen technology, screen refresh rate, resolution, and additional functions such as presence of disc drives and number of tuners). When a manufacturer produces an appliance with the best energy efficiency performance (during use-phase) within its Top Runner category, all other appliances are required to reach that level within a specified time scale. In the case of TVs, the Top Runner approach is still based on the on mode power/screen size, although it uses the screen diagonal rather than screen area.

Characterising policy stringency: relative to and against an aggregate data set of 10,000 TVs

To assess the relative stringency of the policies, the thresholds were plotted on axes of screen area (square centimetres) versus maximum on mode power (Watts). To achieve a fairer comparison, the thresholds for China were adjusted by an empirically derived factor that aimed to take account of the difference in TV sample set up (see [5]). Furthermore, an aggregate data set was assembled consisting of on mode power and characteristics of over 10,000 TVs. This was drawn from the data sets of the Australian government, US ENERGY STAR and the California Energy Commission. The aggregate data set was judged to be highly representative of the US/Australia market for 2012 to

2014, and sufficiently indicative of the global market for worthwhile policy comparison. The products in this aggregate data set are shown in the charts inset into Figure 5 and Figure 9.

Relative stringency of regulatory requirements

Regulatory requirements were found to be set at a power demand three or four times higher than the best models on the market and thresholds are set across a very wide range of performance levels. Figure 5 illustrates the range in the main MEPS in force internationally, from the least efficient (EU 2010) to the most stringent (China 2013).

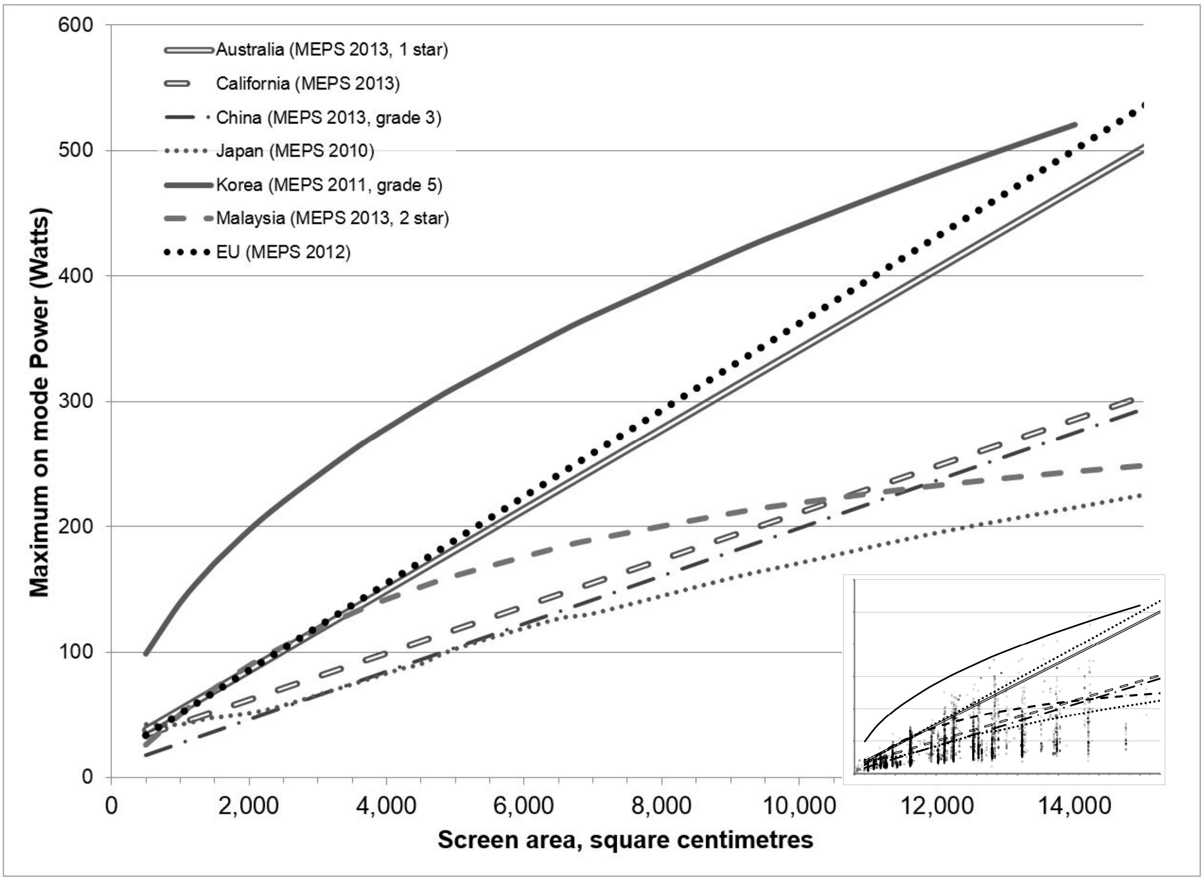

Figure 5. Examples of (MEPS) applicable to all TV types, except for China for which the LCD TV threshold is shown. The inset graph at bottom right shows an identical graph together with the performance of over 10,000 TVs in the aggregate data set and is included purely to indicate the broad spread and density of data points across the identical lines shown in the larger graph [5].

Australia was the first region to regulate TVs in 2009. Compared to the prevalent TV efficiencies on the market, most MEPS have a limited impact on the 2014 market (see Table 1). The wide range of efficiency on the market allows significant scope for them to be tightened whilst retaining a wide consumer choice.

The varying levels of ambition are illustrated shown in the table below.

Table 1: Proportion of TVs in the aggregate data set that fail to meet the MEPS level set in each economy [3].

Australia	California	China*	Malaysia	EU 2012
10%	15%	36%	7%	3%

*Note that figure for China includes additional uncertainty due to differences in set up of screen luminance – whilst data was normalised to take account of this, accuracy has not been proven.

Relative stringency of energy labelling requirements

Whilst ambition is essential in energy labelling in such a fast improving market as TVs, it is often lacking. The highest efficiency classes in energy labels of some countries/regions were found to coincide with the most stringent MEPS in others. As a result of this disparity, high proportions of products are quickly able to populate these upper classes. Some regions quickly lose a number of efficiency classes from their label scheme due to local MEPS being specified higher up the labelling scale.

Figure 6 shows the range of efficiencies covered by the current labelling schemes in Australia, EU and China, where the upper boundary is the highest efficiency threshold; the lowest boundary is the lowest efficiency threshold. The EU and Australia/New Zealand schemes extend to differentiate TVs of much higher efficiency levels (lower portion of the graph) than that of China and of other economies not shown in the figure.

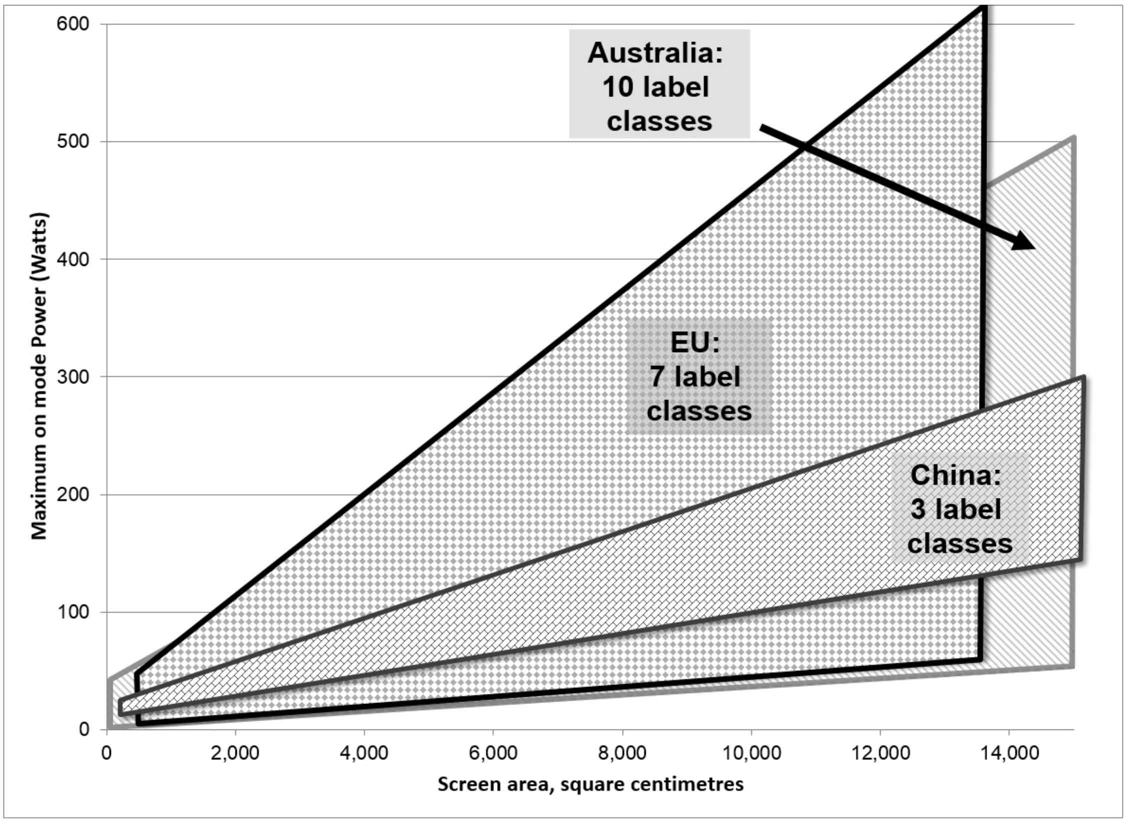

Figure 6. Range of energy classes in labelling. The shapes enclose the upper and lower boundaries of the energy label schemes for EU, China and Australia/New Zealand [5].

The underlying reasons for differences in the level of ambition between economies include limited budgets for research; stage of development of the local evidence base; regional politics; timing of policy and test method update cycles; local product mix and technologies as well as economic concerns.

Towards internationally-comparable and aligned representative efficiency thresholds in policy

As a result of this analysis, a set of five benchmark performance levels have been proposed that policy-makers can use as a foundation for setting their own local policies and label schemes – called reference thresholds (RTs), as shown in Figure 9. The principle of these globally applicable levels is inspired by similar systems already successfully implemented for electric motors (IEC efficiency levels

IE1 to IE5) and for external power supplies (international efficiency mark I to VI); and also the set of international efficiency reference curves proposed by SEAD in 2013 for distribution transformers [8].

The five reference thresholds shown in Figure 9 are intended to provide an 'international ladder of performance', ranging from class RT1 that could be selected as a minimum requirement (or RT2), up to high performance levels for incentive policies at class RT4 or RT5. Labels and MEPS can be selected at locally appropriate levels, but are globally coherent if based on these reference thresholds. The set also provides a clear policy upgrade path, moving up the ladder of levels. This means they are easier and more cost-effective to enforce, which benefits both manufacturers and policy-makers. The approach taken allows for an unpopulated aspirational class better than RT5 to be developed, RT6, and so provide an incentive level for future technology and efficiency improvements.

Whilst the proposed thresholds shown in Figure 9 and described below are believed to be a good initial balance, it is possible to adjust all the factors in the proposed formula to suit a particular or unusual market or if, for example, a less stringent line might be appropriate in a developing economy. After review of national data, policy makers could adjust RT parameters for a fit to their market – although this would diminish other benefits of harmonisation such as lower compliance costs for manufacturers.

Definition of reference thresholds

Insights into existing television policy and market data suggest that a reasonably flat curved threshold best reflects actual TV performance. The hyperbolic tangent (“tanh”) formula similar to that used in ENERGY STAR TVs draft Version 7 (shown in Figure 7) enables such a curve to be defined.

$$Power = 65\tanh\big(0.02 + 0.0005(screenarea - 140)\big) + 15$$

Figure 7. Equation from ENERGY STAR version 7.0 specification for televisions [7]

A fixed baseload power allowance is proposed in the formula to account for the power demand necessary to drive the electrical circuitry. This is independent of screen size. A careful choice of baseload allowance is necessary to ensure that appropriate proportions of smaller TVs are able to meet requirements. In order to create a number of different reference thresholds, a variable called Z_{class} is inserted. In addition the equation is converted to metric square cm units. The resultant equation defined as a basis for reference thresholds is shown below:

$$Power = ABCfactor * Z_{class}\big(65\tanh\big(0.02 + 0.0000775(screenarea - 900)\big) + 5\big) + 7$$

Figure 8. Equation for reference thresholds [5]

The terms in Figure 8 are applied as follows:

- *ABCfactor* is the adjustment to account for whether ABC is taken into account in the declared data or not – and/or to account for differences in the way ABC power calculations are specified under different regional policies.
- Z_{class} is the multiplication factor used to set each separate reference threshold (one Z_{class} factor produces the RT1 line; another produces the RT2 line etc).
- Tanh is the hyperbolic tan mathematical function used to define the curve; tanh provides a curve shape that correlates with what is arguably desirable from a policy perspective (see discussion below).
- *Screenarea* is the visible screen area measured in cm^2.
- ‘7’ is representative of the fixed baseload in W which does not change with efficiency class.
- ‘5’ is the variable part of the baseload which changes with the efficiency class.
- The other factors (65, 0.002, 0.0000775, 900) are proposed to define the curvature of the tanh function to match the data and fairly distribute the efficiency class across the screen sizes.

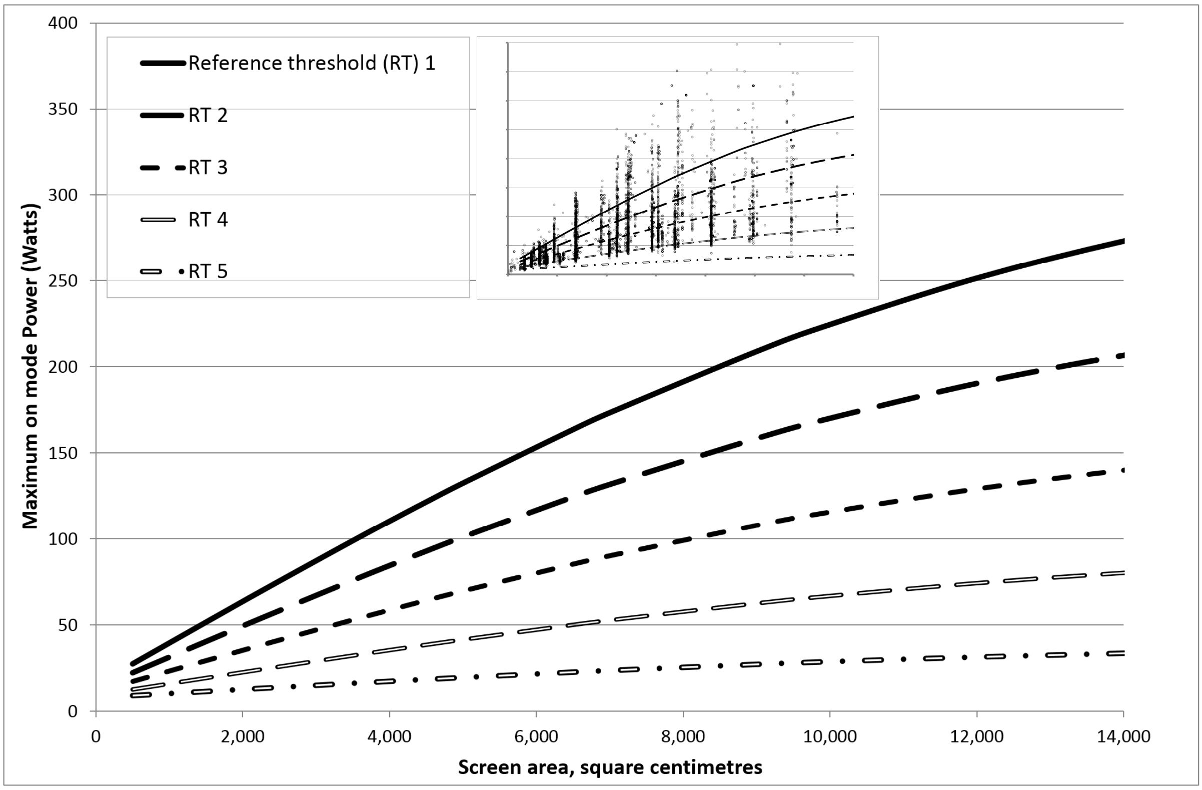

Figure 9. Proposed set of globally relevant reference thresholds (RT) for policy-makers: RT1 (least stringent) to RT5 most stringent. The inset graph at top centre shows the identical graph together with the performance of over 10,000 TVs in the aggregate data set and is included purely to indicate the broad spread and density of data points across the lines [3].

The resultant policy lines mimic the average performance curves for current and emerging television technologies, allowing for appropriate stringency for both larger and smaller screen sizes. The thresholds are screen-size and technology neutral to avoid restricting innovation. There are no allowances for the number of tuners or for additional functionality such as hard drives, as such extras are not considered a core part of the TV service.

Tailoring reference thresholds to regional circumstances

The baseload value of ‘7’ is a proposal that fits current TV data, but should at some point in the near future be revised downwards (e.g. to 5W) to reflect the diminishing contribution of signal processing and other basic functionality to the total consumption of a TV. In addition, one factor that might have previously justified having a reasonable baseload is that unmodified performance lines or curves can be punishingly (or even prohibitively) stringent for small screen TVs. However, the market for very small TVs is collapsing in most regions due to being superseded by tablet computers. Some APEC countries and developing countries may continue to have fairly small screens where the size of accommodation is limiting. The variable baseload factor of ‘5’ will remain important as it is not subject to the market changes applicable to the fixed baseload.

The term ABCfactor is necessary to take into account whether ABC functionality is allowed under the test methodology proposed to underpin the policy - and therefore whether the energy consumption declared by manufacturers has been reduced under the influence of ABC control. If a given data set does not allow ABC to be taken into account, then the reference thresholds must be raised (made less stringent) by around 20%. Hence the ABCfactor has to be set equal to 1.2, if the other numerical factors remain as proposed above. If the data set/market declares data that does take into account ABC then no adjustment is required and the ABCfactor is set to 1. The EU Energy label allows the power consumption to be reduced by 5% if ABC is enabled out-of-the-box. Therefore, the ABC factor should be reduced by 0.05 from the no ABC case, ie ABCfactor 1.15.

Table 2. ABC factor definition [5]

ABC approach	*ABCfactor*
If the policy and data set does not allow ABC to be activated when calculating on power	1.2
If the policy allowance for calculating ABC on power is the same as ENERGY STAR (ABC is allowed)	1
EU Energy label policy with 5% reduction for ABC	1.15

In order to set the reference thresholds (RT1 to RT5), the Z_{class} variable can be defined as in Table 3. This numbering approach allows for the addition of more ambitious classes over time through insertion of values for Z_{class} lower than 0.4.

The relative ambition of the proposed reference thresholds is illustrated in Figure 10, in relation to the EU MEPS of 2012 and the Australia / New Zealand label thresholds for 6 stars and for 10 stars, which together virtually span the worst to the best (respectively) of the 2014 TV market.

Table 3. Reference thresholds as defined by the equation term Z_{class} [5]

Reference Thresholds	**Z_{class} value**
RT 5 Highest performance threshold (aspirational)	0.4
RT 4	1.1
RT 3	2
RT 2	3
RT 1 Lowest performance threshold	4

Whilst representing a wide range of efficiencies, the aggregate data set which has been used to define these thresholds is mainly from Australia and the USA, and so may not accurately represent all markets. Reference thresholds should take into account local product mix and technology availability. It is possible to adjust all the factors in the proposed formula: for example, for a starting MEPS in a country with no previous TV policy, a less stringent line than RT1 might be appropriate. Policy makers should therefore compare their own national television efficiency data with the RT thresholds. Given a more comprehensive data set, the RT thresholds could be adjusted to better reflect global TVs, but those explained in the full report make a very good starting point for most economies.

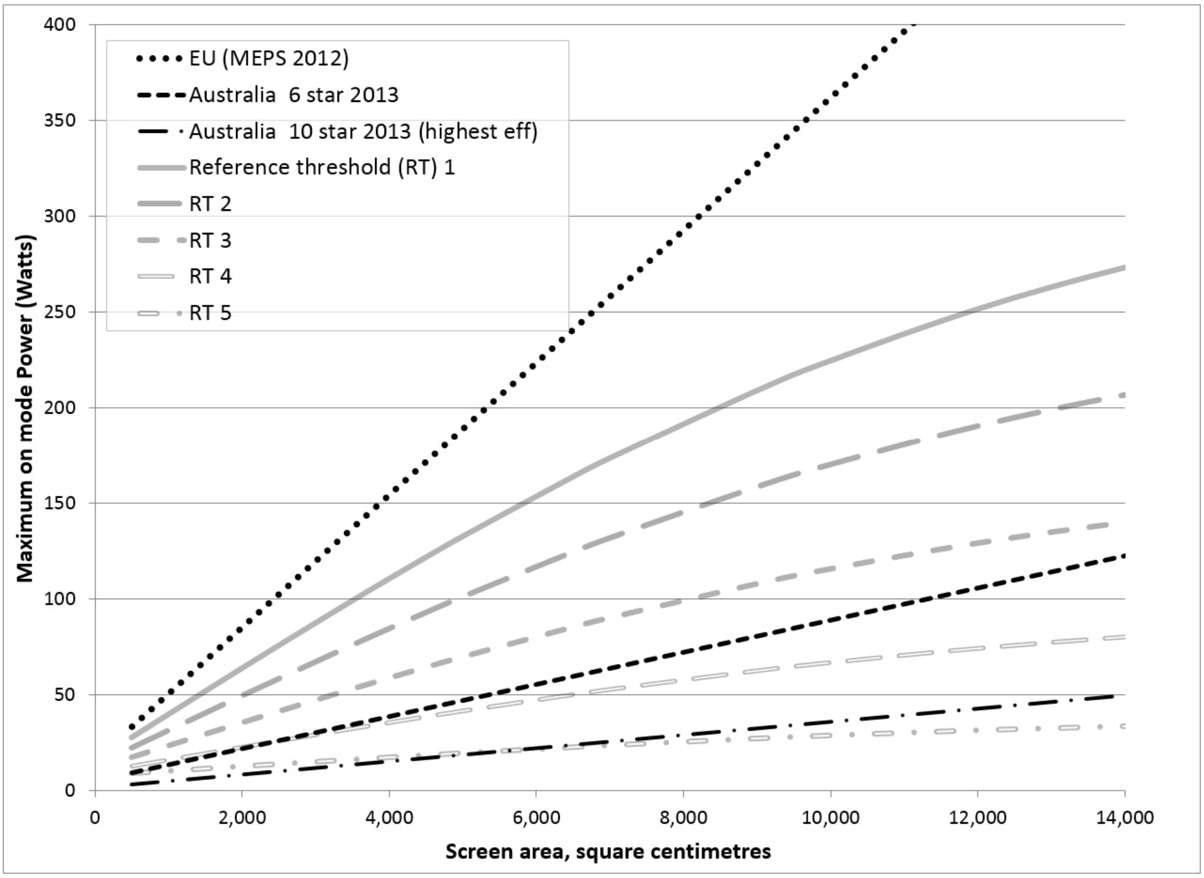

Figure 10. Stringency of proposed reference thresholds (RTs) as compared with EU MEPS (2012) and the Australia / New Zealand thresholds for 6 stars and 10 stars [5].

Catalysing policy-maker involvement and international collaboration to implement recommendations

Productive interaction between policy makers and manufacturers is a key factor. The process of defining policy is inherently dependent on the availability of good quality data. For example a typical MEPS development process can depend on definition of a "best fit" threshold equation to be applied to the market more than six years into the future, based on data that is likely to be at least two years out of date when a regulation becomes law. Therefore, manufacturers should ideally, for their long term benefit, provide as much predictive data as possible on the energy and resource efficiency trends in display products. This is particularly important where stringent requirements for larger screens may be introduced, as these are also the segment of the market where technology innovations with corresponding initial energy impacts may be introduced.

The field of energy efficiency policy for televisions is one of the very few for which global harmonisation of test methodologies, and even performance thresholds, could be made a reality within a few years. This paper highlights a framework for policy planning that could help to bring about this global coherence to benefit policy makers and manufacturers.

We suggest that these concepts could assist policy makers to achieve cost-effective efficiency improvements in televisions. The excel spreadsheet used for this analysis could be refined into a user-friendly tool allowing input of regional data and easy adaptation of reference threshold formulae to adjust stringency against global and local data. Training could be made available to policy makers on the tool to encourage its use.

Key to catalysing policy-maker involvement will be international collaboration, building upon current efforts to benchmark the performance of televisions in order to motivate policy makers to improve regulatory requirements toward the best established MEPS levels based upon evidence of high product performance levels in other markets. Benchmarking activities already addressing televisions include IEA 4E, CLASP and the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative. Other groups involved in policy development that it will be important to engage include the APEC Expert Group for Energy Efficiency and Conservation (EGEE&C), and the Standards Coordination Community of Practice.

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Consumer Behaviour

Smart Homes and Smarter Consumers: How the Internet and Home Area Networks Can Enable Energy Efficient Behavior

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Abstract

Residential Smart Grids efforts typically require a massive investment in metering and communications infrastructure that can result in stranded assets through the premature replacement of fully functioning and non-depreciated equipment. However, Boston, Massachusetts-based NSTAR, an electric utility company serving more than 1 million customers, has demonstrated the viability of leveraging existing automated meter reading (AMR) deployments common throughout the U.S. and Europe to mimic advanced metering infrastructure (AMI) capabilities at significantly lower cost. By using home-area networks (HAN) and customer broadband connections to create a two-way communications pathway, the utility has enabled residential dynamic pricing, two-way direct load control, and the provision of near real-time customer information. This paper describes the technology and program/pricing designs and presents final energy savings and peak load reduction findings from the 2,700-customer, three-year smart grid pilot that concluded in 2014.

More generally, the paper reports on the successes and uncertainties in 1) enabling time-differentiated rates without replacing existing metering infrastructure, and 2) integrating with legacy billing and back-office applications. The pilot was part of the U.S. Department of Energy's Smart Grid Demonstration grant program (part of the post-recession economic stimulus package) and is now providing information to policy makers in the state of Massachusetts regarding the merits of a large scale investment in smart meters. The findings are applicable throughout the U.S. and Europe where smart meter investments are pending.

Introduction

Residential Smart Grids efforts typically require a massive investment in metering and communications infrastructure (smart meters[1]) that can result in stranded assets through the premature replacement of fully functioning and non-depreciated equipment. However, Boston, Massachusetts-based NSTAR Electric & Gas Corporation ("the Company" or "NSTAR")[2], an electric utility company serving more than 1 million customers, has demonstrated the viability of leveraging existing automated meter reading (AMR) deployments common throughout the U.S. and Europe to mimic advanced metering infrastructure (AMI) capabilities at significantly lower cost. By using home-area networks (HAN) and customer broadband connections to create a two-way communications pathway, the utility has enabled residential dynamic pricing, two-way direct load control, and the provision of near real-time customer information. [1]

NSTAR developed and implemented a Smart Grid pilot program beginning in 2010 to demonstrate the viability of leveraging existing AMR deployments to provide much of the Smart Grids functionality of AMI, but without the large capital investment that AMI rollouts typically entail.[3] In particular, a central objective of the pilot was to enable residential dynamic pricing (critical peak rates), time-of-use (TOU) rates, and two-way direct load control (DLC) by continually capturing AMR meter data transmissions and communicating through customer-sited broadband connections in conjunction with a standards-

[1] "Smart meters" is a common term used to describe the customer-sited equipment that is part of an "intelligent metering system", defined as "an electronic system that can measure energy, consumption, providing more information than a conventional meter, and can transmit and receive data using a form of electronic communication." [2]

[2] In February 2015 NSTAR, its parent company Northeast Utilities, and all subsidiaries rebranded themselves as Eversource Energy.

[3] In its 2008 report to Congress on advanced metering, the Federal Energy Regulatory Commission (FERC) cautioned regulators and utilities to protect against functioning, non-depreciated assets (such as AMR investments) from becoming obsolete. [3] U.S. utilities have already invested in tens of millions of AMR meters, accounting for approximately 25% of all meters nationwide and 80% of meters in the Northeast. [4]

based HAN. This enabled recording of interval consumption data and transfer of data to NSTAR via a two-way communications pathway, which was also used for sending load control signals and measuring demand response load impacts.

By the official start of the pilot in January 2012, NSTAR had enrolled approximately 3,600 customers and ultimately installed the enabling Smart Grids equipment at roughly 2,700 homes. As of the end of the pilot in December 2014, approximately 1,500 customers remained enrolled, or roughly 57% of initial participants.[4]

Pilot Programme Experimental Design

The pilot program offerings to customers consisted of 1) a set of new rate options and 2) a set of technologies to enable interval metering, provision of enhanced customer information about pricing and electricity consumption, and (for some participants) automated load response. Each of four customer test groups in the pilot received a unique combination of rates and technologies in order to test hypotheses regarding the impact of technology on load reduction, energy consumption and the interaction of various technologies and rate structures. Table 1 presents a summary description of the four test groups, including the number of participants in each group.

Table 1. Smart Grid Pilot Customer Test Groups

#	Test Group	Description of Test Group[a]	AC Load Control[b]	Number of Participants
1	Enhanced Information	Access to information on energy consumption only; standard rate		1,021
2	Peak Time Rebate	$5 (€6) rebate for automated participation in "critical peak" events via NSTAR control of a smart thermostat; standard rate	☑	422
3	TOU Rate plus Critical Peak Pricing (CPP)[c]	TOU rate with CPP; smart thermostat controlled by NSTAR during CPP events	☑	380
4		TOU rate with CPP		894
Total				**2,717**

[a] All groups received an Internet gateway with access to a web portal and an in-home energy display.

[b] Air-conditioning (AC) load control refers to remotely raising temperature set-points of programmable communicating thermostats controlling participants' central AC systems.

[c] The TOU peak supply price was more than double the standard supplier charges, while the off-peak rate was approximately 60% of the otherwise applicable supply rate. This was a two-tier TOU rate with no shoulder period.

Source: NSTAR

In place of the standard electricity rate, nearly half of all participants in the pilot (Groups 3 and 4) received service under one of the following two new rate designs:

1. **A new TOU rate with CPP for events called by NSTAR.** NSTAR established peak period TOU and CPP rates significantly above the standard residential basic service rate in order to provide an effective price incentive for customers to shift usage off-peak. The TOU peak supply price was in effect between 12.00h and 17.00h in the summer months and between. 16.00h and 21.00 in winter. Peak period pricing was roughly double the off-peak price, and the CPP rate was significantly higher still, at nearly seven times the off-peak price.[5]

[4] NSTAR conducted a "pre-launch" of the pilot with about 200 participants in 2011. The official commencement of the pilot, January 2012, was determined by agreement with the U.S. Department of Energy (DOE), which co-funded the effort as part of the Smart Grid Demonstration grant program (part of President Obama's post-recession economic stimulus package).

[5] Illustrative electricity prices in the pilot were $0.13/kWh off-peak, $0.25/kWh on-peak, and $0.90/kWh during CPP events. Actual prices varied over time depending on the wholesale cost of electricity.

2. **A peak time rebate overlaid on the standard applicable rate,** with a pre-established rebate amount awarded to customers who utilized automated thermostat controls or an automated AC load control switch to reduce load during critical peak events.[6]

There was also one customer segment (Group 1) that received a base suite of in-home technology (see below) but stayed on their otherwise applicable standard rate, which allowed NSTAR to assess the achievable load reductions from a technology-only option that did not require customers to change rates.

Smart Grids Technology

The technology architecture was designed to leverage existing, deployed AMR meters by connecting these meters to NSTAR and the relevant NSTAR internal processes through a set of in-home, cloud-based, and back-office technologies. In this way, the AMR meters were intended to provide AMI-like capabilities—such as the ability to provide billing information for CPP programs as described above or providing interval consumption data to participants—but without the cost of a complete AMI infrastructure deployment.

The technology deployed to provide these capabilities is shown in Figure 1. The architecture consisted of several pieces of in-home technology that communicated with each other wirelessly—including with the customer's AMR meter[7]—and which then connected to a cloud-based technology platform via customer- provided broadband. The cloud-based technology platform in turn connected to NSTAR via a secure Internet connection and was integrated with several of NSTAR's back-office systems to provide the required capabilities for the Demonstration. The in-home equipment and technology platform were provided by Tendril.

This technology infrastructure was intended to establish a reliable backhaul communications pathway from the meter to NSTAR's internal systems and allow meter reading resolution suitable for TOU and CPP rate plans. The deployed equipment also enabled automated load control of central air conditioning and provided customer information via in-home displays and an Internet-based web portal.

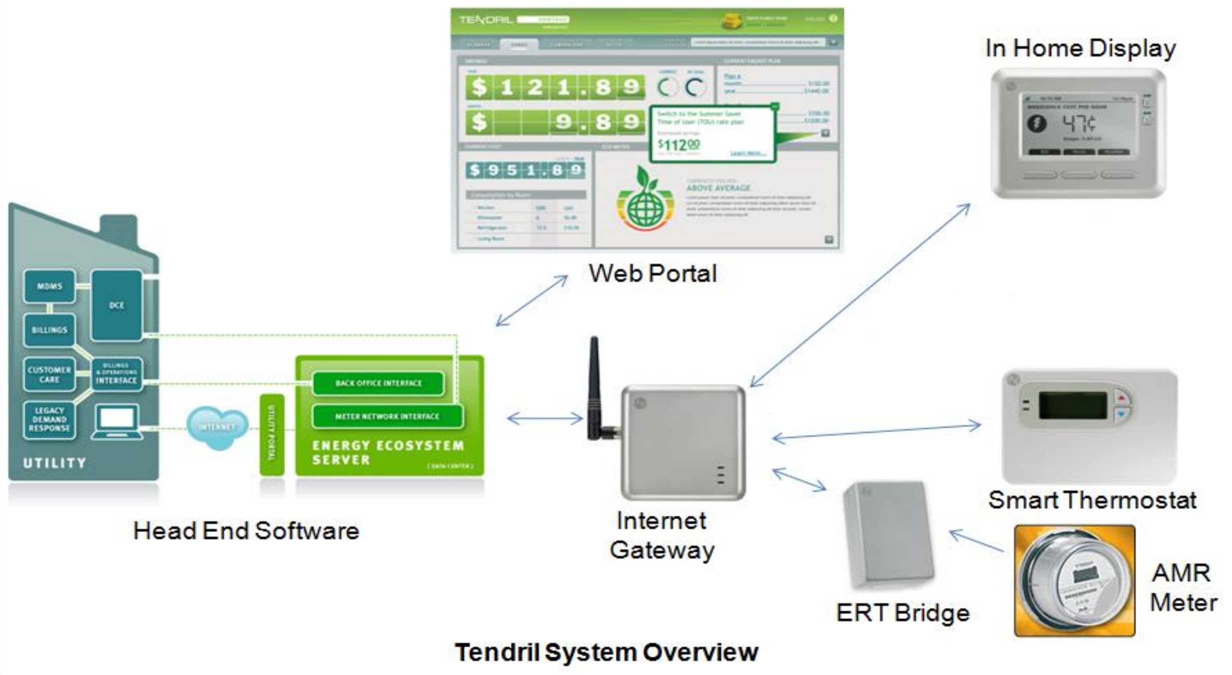
The technology shown in the figure can be divided into the following functional categories:

- **Customer-facing technology:** These are elements that allowed direct communication with pilot participants and provided consumption, pricing, and other information to the participants. These elements were the focus of much of the customer survey work performed in the evaluation.
- **In-home infrastructure:** These are elements that enabled the communication pathways within the home via ZigBee low-power radio connectivity and provided communication, via the customer- provided broadband, to the cloud-based platform capabilities and the NSTAR back-office systems.
- **Cloud-based platform:** Provided the central control and management functionality for the pilot system
- **Utility back-office systems:** NSTAR systems that were integrated to provide the necessary functionality to run the pilot

[6] The peak time rebate was a no-risk alternative intended to achieve peak demand reductions by providing customers with a financial incentive to reduce load during critical events called by NSTAR. Customers retained their usual rates but would receive rebates for reduced consumption during events. All customers participating in the critical peak rebate offering were required to have central air conditioning and were provided a smart thermostat that enabled automated load control by adjusting AC temperature during events. During events, thermostat settings were remotely raised by NSTAR to between 1 and 6 degrees F (NSTAR determined the setback for each event). Participants could opt out of any individual event, foregoing the $5 rebate each time they did so.

[7] AMR meters send wireless signals that can be read by meter readers or trucks passing in the vicinity of the home. Unlike with always-connected AMI meters, data from AMR meters must be picked up manually. The pilot solution overcomes this limitation by using in-home equipment and existing broadband connections to continually pick up the data and automatically transmit back to the utility.

Figure 1. Components of the Smart Grid Technology Platform



Source: Tendril

The customer-facing technology consisted of the following three elements:

- **Web portal:** The *Tendril Vantage* is a browser-based Internet portal that enabled monitoring, management, and control of energy consumption on smart ZigBee-enabled devices in the home. Among its features, the web portal allowed customers to view and manage household energy consumption, compare consumption to other households with similar demographics, and receive messages from NSTAR.
- **In-home energy display (IHD):** The display is a digital wireless (ZigBee protocol) device that showed real-time power demand, billing-period electricity consumption and cost, the current TOU electricity price or critical event status (if applicable), and other related information. The display was used by customers to help identify measures to lower consumption, and it served as an additional communications vehicle for NSTAR to inform customers of critical events.
- **Smart thermostat:** Participants who received a wireless (ZigBee protocol) smart thermostat were able to program temperature set-points either manually or via a user interface on the Internet. At the onset of a critical event, NSTAR sent a signal to increase the temperature setting on thermostats by either 3 or 5 degrees for the duration of the event. (The amount varied by event.) Any changes made by customers to the thermostat settings supersede the previous load control signal.

The other in-home infrastructure consisted of the following elements:

- **AMR meter**: The customer's automated meter reading meter—already deployed at the customer site prior to the pilot—measures customer consumption and transmits the readings via Encoder Receiver Transmitter (ERT)[8] radio signal at frequent intervals so that they can be picked up by drive-by utility trucks for monthly readings.
- **ERT bridge**: This element was able to read the ERT signal from the AMR meter to get household consumption data, nightly or as requested by NSTAR, and to translate that signal into ZigBee radio signal to communicate with the other in-home devices, which all communicate via the ZigBee protocol.

[8] ERT is low-power radio operating in the 900-megahertz (MHz) ILM band and designed specifically for drive-by meter reading applications. ERT is a trademark of Itron, Inc.

» **Internet gateway**: All participating homes were equipped with an Internet gateway connected to a wireless (ZigBee protocol) HAN. This gateway transmitted consumption data from the meter to NSTAR via the ERT bridge and allowed communication back to in-home energy displays.

These technologies constituted the Smart Grid from the **customer perspective**. They provided feedback on energy consumption (via an in-home display or a web portal) and offered participants the convenience of remotely controlling household temperature. The automated response to critical events was intended to allow for greater load reductions and bill savings.

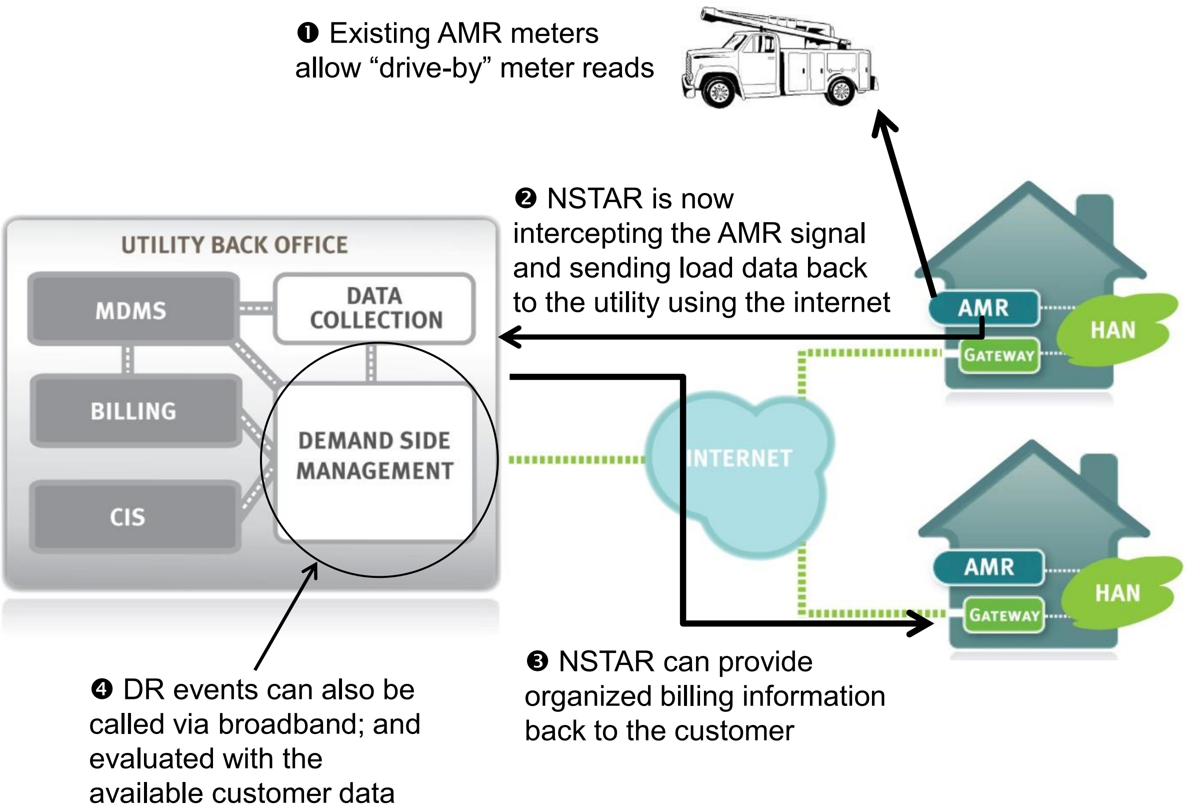
The utility head-end and back-office elements consisted of the following elements, also shown in Figure 2.

» **Tendril Energy Ecosystem Server**: Provided the central control and management functionality for the Tendril system, including Internet connectivity to the participant household equipment and to the NSTAR back-office systems via secure connection. It also performed such functions as enrolling and tracking status of pilot participants, collecting consumption data, and managing demand events.

» **Utility Back-Office Systems**: These are production systems as well as pilot-specific systems at NSTAR that were integrated to perform necessary functions for the pilot, including using pilot data for billing and managing participant calls at the call center.

A more utility-centric view of this functionality is shown in Figure 2., which shows the various communication pathways between the utility and the home. The Tendril platform provided the capability of utilizing the customer's existing Internet connection as the communications backhaul.

Figure 2. Communications Pathway to and from the Customer Home



Source: Tendril, adapted by Navigant

This technology architecture was intended to allow NSTAR's existing AMR meters to provide many of the key capabilities delivered by the newest AMI systems, without undergoing the cost and disruption of upgrading to a new AMI system and retiring the AMR assets before the end of their useful life.

Findings: Energy and Peak Demand Savings

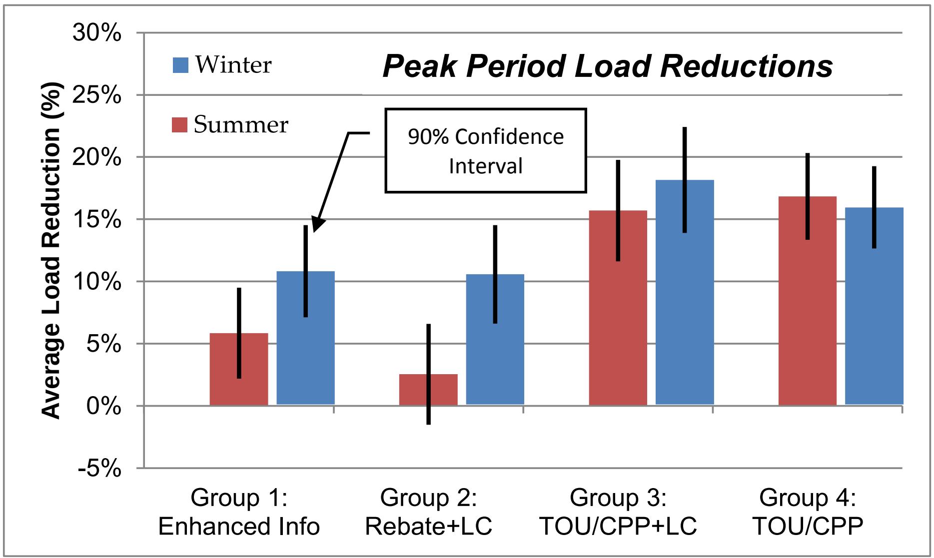
The combination of time-variable rates and enabling technologies allows for testing of various hypotheses regarding the energy savings impact of individual rate structures and technologies. For example, Test Groups 3 and 4 (TOU/CPP rates) can be compared to the control group to assess the impact of a TOU rate on peak period consumption as well as the impact of the high-priced critical peak event relative to normal peak hours. Comparing Test Groups 2 and 3 then allows for measurement of how a critical peak *rebate* influences consumption relative to a critical peak *price*.

The estimation of the consumption impacts of all four test groups required hourly meter data collected for each participant as well as for the control group.[9] The evaluation team consolidated the individual time series into a single panel (or longitudinal) data set; that is, a data set that is both cross-sectional (including many different individuals) and time series (repeated observations for each individual). The consumption impacts of all four groups were then estimated using fixed-effects regression analysis with weather normalization.

Based on participant consumption data from January 2012 through December 2013, major findings of the impact analysis include the following:

Peak period impacts. Pilot participants in Groups 3 and 4 were placed on a TOU rate, in which customers were charged a higher rate during the peak period and a lower rate during the off-peak period (all non-peak hours). The rate was intended to encourage participants to shift a portion of their peak period load to the off-peak period. Customers on the TOU/CPP rates (Groups 3 and 4) reduced summer peak loads by approximately 0.2 kilowatts (kW) on average, or more than 15% of their average peak period consumption. Customers on the standard rate also reduced their consumption during peak hours, but only by approximately half as much as customers on the TOU rate. Figure 3 provides the average peak period reductions for summer and winter for each pilot group, as well as showing the upper and lower bounds of a 90% confidence interval of the impact estimate.

Figure 3. Average Peak Period Load Reductions, by Group and Season



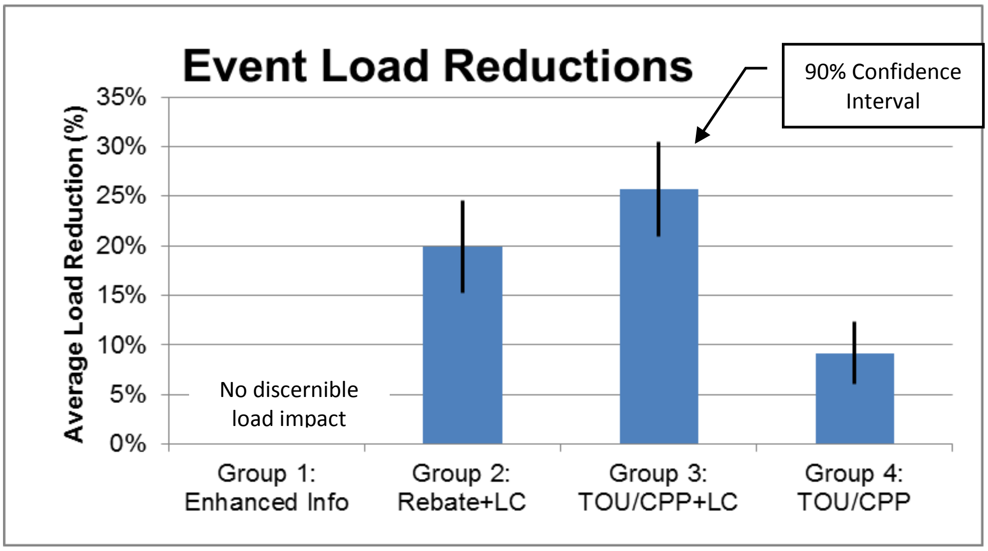
Source: Navigant analysis

Impacts of critical events. NSTAR called a total of 15 summer load control and CPP events during the pilot period. The events varied between either three or five hours in length, with the temperature increase during the event (the increase in the thermostat set point) varying between 3 and 5 degrees

[9] The size and makeup of the control group varied depending on the subject of the analysis. For event impacts, the analysis used participants' own data from non-event days as a basis of comparison. For peak demand impacts, the control group was selected from a limited number (less than 1000) of customers in NSTAR's load research sample for which interval data was available. For energy and bill savings, a matched control group was selected (one match per participant) from a random sample of 10,000 customers.

Fahrenheit (1.6 and 2.7 degrees Celsius). Event impacts varied widely across groups. Participants with automated load control of central AC (Groups 2 and 3) had the largest reductions during events—approximately 20-25% of load, or about 0.5 kW. Participants on the TOU/CPP rate without load control (Group 4) realized modest load reductions of nearly 10% (0.13 kW), whereas, participants in the Enhanced Information group (Group 1) produced no discernible load reductions (Figure 4).

Figure 4. Average Load Reductions During Events

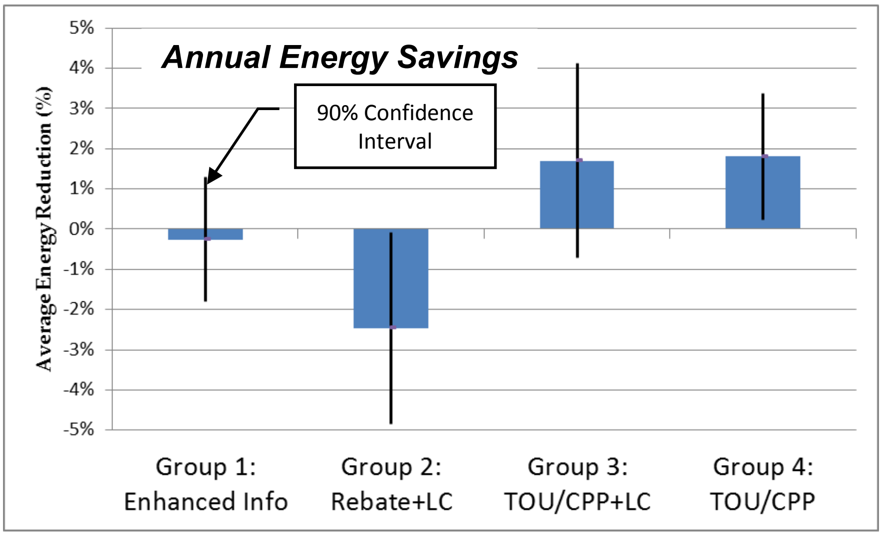


Source: Navigant analysis

Annual energy impacts. While the previous set of results addressed reduced consumption during peak periods, another major purpose of the pilot program was to encourage energy conservation during all hours through increased information about energy consumption, provided by the in-home display and the web portal. The energy impact analysis described below presents estimated changes in energy usage because of pilot participation.

Customers on the TOU rates reduced their (weather-normalized) annual energy consumption by approximately 2%, while the standard rate participants in Groups 1 and 2 saw little change in consumption or an increase in usage Figure 5. All of the energy-impact results have sufficient statistical uncertainty around the estimates to limit generalizations about whether and how much the pilot led to changes in non-peak-period, non-event-related energy consumption.

Figure 5. Annual Energy Savings



Source: Navigant analysis

The relatively wide confidence intervals (crossing or coming close to the zero line that implies no change in consumption) is driven by two factors:

- » The low number of monthly bills available for analysis. At most, there were only eight summer billing periods and 16 winter periods; and
- » The fact that the point estimates of energy savings are relatively small—between 0 and 2.5% savings. This suggests that even a model that can estimate energy savings to within 2% of total consumption will still show an uncertainty band roughly as large as the savings estimate itself.[10]

Not shown in the above graphic is the fact that savings appear to have decreased as the pilot progressed, with summer 2012 savings exceeding summer 2013 savings (roughly 2% savings vs. no savings). Winter months showed a similar pattern, with a modest savings in January through May 2012 becoming a modest increase by fall 2012.

Key Learnings from the pilot

This evaluation of NSTAR's Smart Energy Pilot has identified several broad themes, based on the specific findings of the impact evaluation (discussed above) and a review of pilot program processes, technologies, participation, technology performance, and customer viewpoints. Key learnings from the pilot with respect to customer interest, technology performance, participant engagement, and energy and demand impacts are as follows:

1. **Customer interest.** *Smart Grid offerings may appeal to only a limited segment of the population—principally educated, affluent, and technologically savvy customers—absent long-term education efforts and innovative marketing approaches to pique the interest of the broader customer base.* Customer interest in the pilot was relatively strong initially, with response rates to NSTAR's direct mail and email marketing efforts of 4% and 7%, respectively, compared to the 2% to 4% response rates typically seen in Smart Grid program recruitment. While the overall response rate was high, customers expressing interest and enrolling in the pilot were primarily highly educated, affluent households, often with an expressed or demonstrated interest in internet and computer technology. Despite concerted efforts by NSTAR to market all customers in the pilot territory, low-income customers did not enroll in high numbers, as evidenced by only about one percent of participants being on the low income rate and roughly four percent reporting income below 60% of the median level for their household size.
2. **Technology performance.** *The pilot demonstrated that the technology architecture is capable of AMI-like features through the collection of interval meter data, but that it is not yet viable for the widespread provision of customer information and dynamic rate tariffs.* While the pilot generally demonstrated the capability to deliver on these objectives for many customers, most of the time, the lack of reliability remains a major functional limitation. The following are among the significant reliability issues that must first be addressed before a similar system is deployed on a large scale as an alternative to revenue-grade metering:
    a. Usability of the technologies, from the thermostat that was difficult to install, to the accessibility of customer data, which was not available on mobile applications;
    b. Data intermittency from HAN system disconnections and temporary failure of back-end systems, both of which led to gaps in meter data that rendered TOU rates incomplete and resulted in defaults to the flat rate;
    c. Complexity and inconsistency of meter data validation/estimation process, which caused data gaps and misalignment of intervals, resulting in differences in monthly consumption estimates between the interval data from the pilot architecture and the monthly drive-by reads from NSTAR's standard meter reading procedures.

    Advances in technology since the initial pilot Soft Launch in 2010—such as wireless gateways using IP, extended on-site storage of information, and mobile phone apps—suggest that at least some of the issues raised by the pilot may be substantially resolved and that a similar

[10] Estimation of energy savings from "behavior" programs, such as the Smart Energy Pilot typically utilizes sample sizes in the tens of thousands in order to achieve more precise estimates of impacts.

approach to reading the AMR meters but leveraging these newer technologies might be more effective, and possibly lower cost.

3. **Participant engagement.** *Participant perspectives on the pilot were generally positive, but the trend of diminishing interest over time raises questions about the long-term impacts of a future dynamic pricing offering, especially if provided to all customers on an opt-out basis.* The positive customer reviews of the pilot are a testament to the strong delivery and positive messaging that NSTAR put forth from initial marketing to final closeout of the pilot. However, this is offset by the decline in enrollment by more than one-third over less than two years, and the decline in participant engagement (even among those who remained in the pilot, as evidenced by declining energy impacts and reduced use of the web portal and in-home displays). The implication is that a program requiring sustained engagement may not be for all customers; even those initially enthusiastic may lose interest over time.

   However, it is also possible that some of participants' declining interest and engagement may be experiment fatigue with a pilot environment. Participants knew there was a fixed period of experiment and then things were back to 'normal'. If 'normal' becomes a system of universal time varying electricity rates where electricity costs predictably vary by time of use, engagement will have different stakes and customers may engage differently as well.

4. **Energy and demand impacts.** *Pilot impacts were apparent for peak demand, but inconclusive with regard to whether the provision of energy usage information enables significant reductions in overall energy consumption.* The pilot's technology and rate offerings were designed to enable three types of reduced consumption: 1) peak period load reductions, 2) load curtailments during critical events, and 3) overall reduction in energy consumption (monthly/seasonally/annually). Consistent with industry experience, the pilot successfully demonstrated peak period reductions, particularly for customers on TOU rates. NSTAR specifically designed peak rates to be significantly higher than off-peak rates in order that participants could reduce their electricity bills by shifting load away from peak hours. Load curtailment during critical events was also successful, particularly where long-established DLC of central air conditioners was employed. Less certain is whether the Smart Grid's provision of access to energy consumption information successfully encourages and enables customers to save energy over the long term. Energy savings was minimal (2% on average for those on TOU rates, and a statistically insignificant change for others), with all groups showing a marked decline in savings after the first nine months of the pilot.

Implications for the Use of Existing Meter Stock for Smart Grids Services

Taken collectively, the above learnings have several broad implications for the future of possible customer-facing Smart Grids offering based on AMR meters and customer broadband:

1. **The pilot achieved its technology validation objective, including verification that "smart meter" functionality can be achieved without deployment of an advanced metering infrastructure.** The general pilot architecture approach, after improvements in technology and data management, can be an effective, low-cost way for NSTAR or other utilities with AMR meters to enable energy information and TOU rates for customers who want it, without investing in new metering infrastructure for all customers.
2. **The market offering must communicate to customers that they have an important role to play in ensuring the system functions as designed.** Customers have a reciprocal role in that NSTAR will need customers to help maintain the operability of the in-home devices and broadband communications in order for NSTAR to provide usage information and to bill customers on dynamic rates.
3. **A successful offering of dynamic rates and visibility of customer usage information will require an aggressive and intelligent marketing effort to reach customers and engage them to act over a sustained period of time**. Keeping customers engaged after the initial few months or first year of a Smart Grid offering will likely require the incorporation of apps for mobile devices where energy information is more readily accessible and occasional push messaging and event notifications can engage customers without their having to initiate the engagement.

4. **Only a narrow segment of the population is likely to participate or contribute to savings.** The pilot demonstrated that interest among customers is predominantly among more affluent and educated customers, who also tend to be larger customers with more discretionary load. These demographic groups represent only a small share of the population. By contrast, relatively few low-income participants showed an interest or ability to conserve energy.

Conclusions

The residential Smart Grids pilot conducted in the Boston, Massachusetts region by NSTAR has provided a wealth of data on customer perspectives, technology performance, and programmatic impacts on energy consumption. Collectively, this data can inform corporate and policy decisions whether and how to pursue similar endeavors in the future. The pilot has demonstrated the feasibility and promise of residential Smart Grids technologies, while also revealing their limitations and drawbacks.

In particular, the pilot demonstrated the potential to deliver customer benefits by utilizing existing metering infrastructure and broadband communications, provided that (1) technology offerings continue to develop in order to improve usability and reduce data intermittency (2) education and marketing efforts are robust to be able reach customers and engage them to act over a sustained period of time, and (3) the solution is targeted to those customers most likely to embrace and benefit from alternative rate designs and take action by changing their energy usage behaviors. The findings are applicable throughout the U.S. and Europe where smart meter investments are pending. Given that most member states of the European Union have established legal frameworks for smart meter investment in the years following the Third Energy Package, [5] much of Europe is either making significant investments or evaluating the most prudent path forward. [6]

For NSTAR or any other utility in the U.S., Europe, or elsewhere with significant investments in existing metering infrastructure, the decision whether to invest in a future rollout of similar Smart Grids architecture and program offerings must be assessed based on the costs relative to the achievable quantifiable benefits. An important consideration will be who bears the costs and to whom the benefits accrue—to the utility, its participating customers, all ratepayers, or all electricity consumers in the region, who might benefit from lower market prices. For those countries or companies that have not yet committed to the full functionality—and cost—of smart meters, the NSTAR pilot programme provides an interesting alternative that may allow selective investment for customers who most desire a smart metering system.

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How to make efficient use of kettles: Understanding usage patterns

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Abstract

According to a survey by the Energy Savings Trust three-quarters of UK households overfill their kettle, wasting GBP68 million per year. This paper focuses on patterns of behaviour with respect to kettle use and how these could be influenced by providing feedback to make kettle usage more efficient. Firstly, we study how kettles are used across 14 UK households for a two-year period, which allows analysis of seasonal patterns as well as changes due to the holiday season. We also examine usage patterns based on the type of occupant and how their daily routines affect usage. Secondly, a case study is described where a standard kettle has been replaced with an 'eco' kettle during the monitoring period, which allows to analyse if energy consumption has been reduced due to using a more energy efficient kettle. We look at the usage patterns and investigate potential change in behaviour that has occurred since the switch. Our main findings based on monitoring diverse UK homes with a range of kettles, is that the total consumption is less dependent on the type of kettle used, and more dependent on the established household usage patterns and habits. We also show, through our case study, that usage of kettles can be improved by optimising usage patterns to best utilise the type of kettle.

1 Introduction

The roll out of smart energy meters in UK homes is set to begin in 2015 and is planned to be completed by 2020 [1][2]. The goal is to increase the energy efficiency of UK homes by promoting behavioural changes and providing appliance retrofit advice via data supplied from smart meters. Through the feedback that smart meters are able to provide we can aim to educate the consumer about their appliance usage and promote energy positive behaviours.

In this paper, using the data gathered from a two-year field study, we look at the electric kettle, identify patterns of usage, analyse consumption, predict consumption via suitable models and show how kettles could be used more efficiently. The kettle is one of the most (inefficiently) used appliances in the UK as well as the appliance with the highest rates of ownership (according to UK's Department for Environment, Food and Rural Affairs' 2008 report [3] 97% of UK households possessed a kettle). In a survey of 86,000 homes in the UK, by the Energy Saving Trust, it was found that three-quarters of British households admit to overfill their kettle when boiling water and are subsequently wasting £68 million each year. More than nine in ten people (95%) use the kettle every day, with 40% doing this five times a day or more [4].

Kettle is also the main cause of the so-called TV pickup effect, that manifests itself in significant and synchronised usage of appliances during TV programmes' breaks. This is especially a problem in the UK where individual programmes often attract massive audience, and householders use commercial breaks for boiling water and opening of refrigerator door.

Many empirical studies of consumers' attitudes and interactions with energy-consuming appliances have been reported recently [5][6]. Interestingly, despite the fact that kettle usage patterns significantly affect energy consumption, the consumer behaviour with respect to the usage of kettle has not been in the research focus so far. Previous research into the energy consumption of the kettle [7] details the monitoring of energy consumption of the appliance and the different mathematical tools which can be used to model the relationships between consumed power, water volume and temperature during kettle's operation. We build on [**Error! Bookmark not defined.**], but while [**Error! Bookmark not defined.**] focuses on a single kettle, we study a large sample size, analyse how different households use their kettles, and develop and validate generic mathematical models.

In particular, we study the usage patterns of kettle in 14 UK homes over a two-year period. This was enabled by measuring only the timestamped kettle power consumption via a plug monitor that measures active power every 6-8 sec. The monitored houses are of different occupancy and age groups (e.g., retirees, working couples, families with children and single occupants) and possess different types of kettle. These households were chosen with a mix of technical and non-technical backgrounds, and were fitted with energy monitoring equipment (gas, electricity for up to 9 individual appliances), environmental sensors and smart home kit to automate/pre-schedule appliance and heating use. Our analysis shows that kettle usage patterns are semi-regular with clear peak times (morning, evening around dinner) and sporadic usage otherwise during the day. Usage patterns are correlated to working patterns, family size, and age group: working couples will likely have no or only few uses between the hours of 9am and 5pm, while retired couples would have more sporadic usage of kettle.

Since we measure only the energy consumption of the kettle, we also develop mathematical models to predict water volume and temperature in the kettle, based on measured energy consumption. We show the difference between 'smart' / 'eco' and 'dumb' kettles and whether they represent a sound investment in money and environmental friendliness. A 'dumb' kettle is defined as a kettle that boils water to 100°C with no additional 'boil' temperatures and no 'keep warm' or additional functionalities. The case study of the household with the 'eco' kettle also discusses householder's reaction to feedback on their relative energy consumption before and after the introduction of their 'eco' kettle.

The paper is organized as follows. Section 2 reviews the current state of the art on kettle efficiency, design, usage patterns research and feedback design mechanisms. Section 3 describes our methodology. Sections 4 describes our models and results of our analysis. Section 5 discusses a case study involving 'smart' kettles.

2 Background

Kettle design has remained fairly static for many years. This is partly due to the heating element contained in many kettles being as optimised as it can be within reasonable limits. Heating efficiency of the element itself is 100% as the energy supplied is completely converted to heat. However, most kettles are around 80-90% efficient (efficiency is decreased due to heat dissipation and transference to the body of the kettle).

Recently, the market for household appliances has been evolving; suppliers are beginning to term their appliances "smart" in order to entice customers. These appliances usually come equipped with additional quality of life improvements, quicker operation, more preprogramed settings, etc. This has not, however, affected the main body of the kettle and is often located on the baseplate that is used in wireless kettles.

Kettle design has also trended towards producing larger kettles in terms of volume. For example, modern kettles are holding upwards of 1.5 litres, and in some cases, as much as 2 litres which can lead to even more water being wasted by those who habitually overfill. Kettle design partly has a role to play on overfilling: many kettles feature volume indicators; these usually start at the 2 cup level (500ml) as a minimum fill so that there is enough water to cover the element in the increased base area. A person planning to make one cup of tea is effectively wasting at least 50% of the energy required straight away if they follow the filling guide.

Kettles in general have a power rating of 2200-3000 Watts (W). Kettles marketed as "Eco" generally tend to have a lower rated power band (1350 W) but feature a more insulated thermos style design which is intended to keep water hot enough to make another cup or to reduce the amount of reheating required. One such kettle is the Vektra which is a highly insulated thermos styled kettle, meant to provide saving of up to 55% which would make it an ideal candidate to replace a standard kettle [8][9].

Kettles are also not subject to any efficiency labelling guidelines; this means that the consumer may not understand that a lower rated kettle will take much longer to boil than a high rated one but consume the same amount of power. This time distinction however might help encourage energy efficient behaviour as the occupant is aware that the kettle will take much longer to boil if it is over filled. However, a study showed that 86% of people do not choose kettles based on their features but on looks to match a kitchen design/already owned products [10].

Behaviour in regards to filling is something that is simple to change - if the householder first fills the cup they intend to use they are able to minimise any loss through over filling. Analysing people's behaviour may show that people already have developed good usage habits in which case providing kettle retrofit information may be more beneficial in helping to save energy. Variable temperature kettles provide multiple options: in some cases boiled water may not always be the most efficient option or result in the best tasting drink. Many speciality teas and coffee’s recommend temperature ranging from 70 degrees up to 95 degrees (ideal to stop coffee burning). These temperatures represent a reasonable saving especially over the course of a year. Finally, a change to a kettle with a lower minimum fill level may be the best course of action for single occupant households or those with few users. It would also benefit a household where people are actively aware of their energy footprint which makes a kettle, where they can easily see and dictate the water level ideal.

3 Methodology

Since our sensor measures only consumed energy, it is necessary to infer water volume and temperature to provide feedback on possible energy waste. In this section we present the proposed mathematical modelling method whose goal is to infer the amount of water the kettle was filled with only from the total power consumed and the time taken to heat the water from the average UK autumn/winter/spring tap water temperature (8-12°C) to boiling point. The model comprises two parameters, water temperature and water volume, and hence can also be used for summer data when tap water temperatures are above 15°C (typical in the summer). The model is also used to infer if the kettle water has been re-boiled taking into account the duration between boils and the power consumption.

3.1 Mathematical Modelling

Since we cannot directly measure volume of water in the monitored houses, we develop a mathematical model to estimate the level of water in the kettle based on the measured power. Our modelling work is based on a training dataset generated using exhaustive lab experiments which consist of recording kettles’ energy consumption and time duration for different water volume levels and starting/stopping water temperature.

Using three different types of kettle: ‘smart’, ‘eco’ and traditional, ‘dumb’ kettle (which is representative of the majority of the UK market), we carried out 84 experiments collecting data for training and 10 experiments to validate the model for each type of kettle. The experiments studied the relationship among 5 features: time duration, starting water temperature, stopping water temperature, water volume, and power consumption.

Our experimental results obtained by filling the kettle with different volumes of water and stopping the kettle once a particular temperature is reached, averaged over three experimental kettles, are shown in Fig.1. While the starting temperature of the water may not seem important since water is rarely heated from above 30°C degrees, analysing this feature, together with the other features, help determine which model is the most suitable.

It can be seen from Fig. 1(a) that the relationship between the starting water temperature and the consumed power is nearly linear. A similar, close-to-linear, relationship holds between the time duration and the initial water temperature and consumed power (see Figs. 1(b), (c), and (d)). Based on these, we decide to use linear methods to build the model.

In the previous work [**Error! Bookmark not defined.**], we compared three linear methods - polynomial linear [11] (high error), locally weighted linear regression [12] (largest range prediction), and the linear interpolation [13] (limited range) method. The results from [7] indicate that the model with locally weighted linear regression gives the best estimate although linear interpolation has the best accuracy but has a limited range.

Fig. 2 shows the kettle model generated by the weighted linear regression method and the residual error analysis with the x-axis denoting the starting water temperature, y-axis the water volume and z-axis the consumed power. In this model, active power is considered as a hyper-layer and is not shown in the figure. The dots on the left hand plot represent collected data, while the coloured surface is the kettle model.

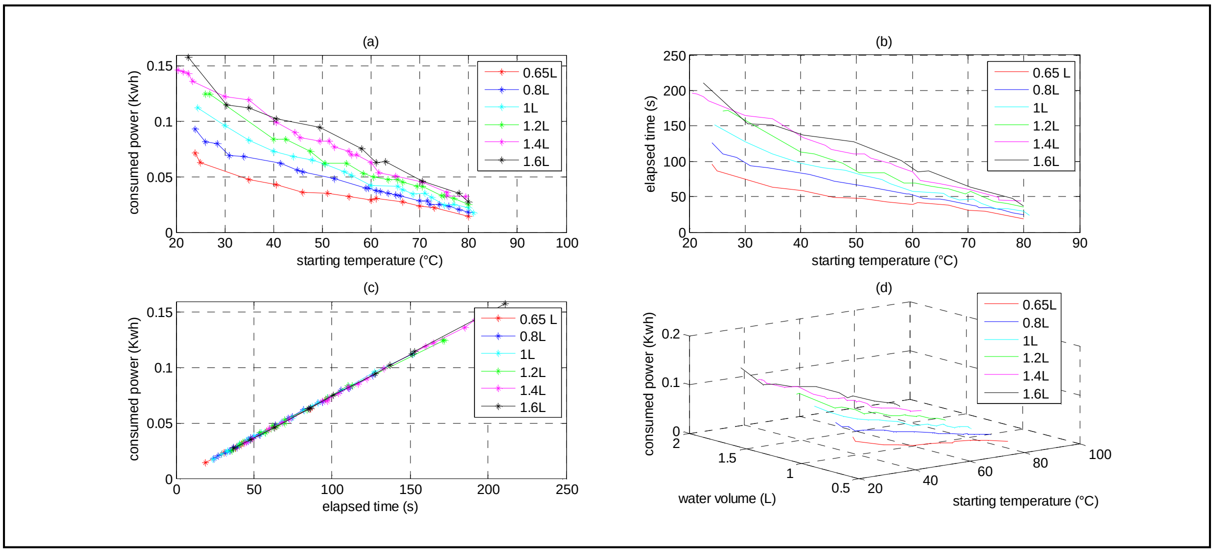


Figure 1: Measured relationships between consumed power, water temperature and volume (in litres (L)) averaged over three experimental kettles.

It can be seen from Fig 2 that there is a good agreement between the data points and the model with insignificant residual error.

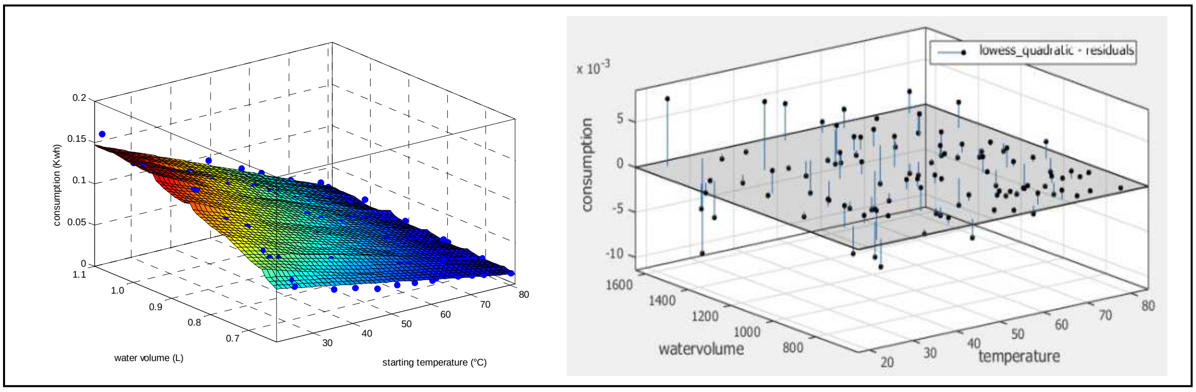


Figure 2: Kettle model and residual error analysis.

3.2 Model validation

Depending on the parameter being estimated, we apply the proposed model in three ways: (1) estimating the consumed power based on the initial temperature and water volume; (2) estimating water volume based on the power consumption and initial temperature; (3) estimating the initial temperature based on the water volume and power consumption. For testing purposes, we randomly select 12 instances of kettle use across each type of kettle using the testing data. Table 1 shows the three different estimations using the proposed model with weighted linear regression.

Table 1: Estimation results

	'dumb' kettle				**'eco' kettle**				**'smart' kettle**			
Test #	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
AP (W)	2668	2710	2694	2683	2604	2083	2062	2381	2612	2493	1855	2373
EC (Wh)	0.13	0.06	0.05	0.05	0.11	0.01	0.02	0.03	0.16	0.06	0.01	0.02
RC (Wh)	0.14	0.06	0.05	0.05	0.11	0.02	0.02	0.03	0.17	0.06	0.01	0.03
EWV (L)	1.54	0.90	1.16	1.36	1.20	0.97	0.94	1.16	1.50	1.53	1.10	0.61
RWV (L)	1.65	0.95	1.10	1.25	1.00	1.00	0.75	1.25	1.50	1.50	1.25	0.50
ET (℃)	29.37	52.04	60.42	61.90	16.88	91.06	86.46	80.20	17.98	69.91	89.79	72.97
RT (℃)	29.5	48	62	64	17	95	90	80	18	70	90	80

AP – Active Power, EC – Estimated Consumption, RC – Real Consumption, EWV – Estimated Water Volume, RWV – Real Water Volume, ET – Estimated Temperature, RT – Real Temperature.

As shown in Table 1, the weighted linear regression model accurately estimates all parameters, for the ‘dumb’ and ‘smart’ kettle. The estimation for the ‘eco’ kettle is the worst, and it is particularly inaccurate when the water is close to boiling temperature (i.e., 90°C), when the error sharply increases to 3.54°C. This can be explained by the extra insulation in the ‘eco’ build, which improves heat retention and speeds up boiling without any additional power. Therefore, this model is suited for most kettles except for those with insulated carafes, such as the ‘eco’ kettle, for some temperature range.

Table 2 presents the prediction errors, averaged over all three kettles, for the results shown in Table 1. The estimation error of temperature is 1.21°C which is considered insignificant, as it does not affect our analysis on usage patterns.

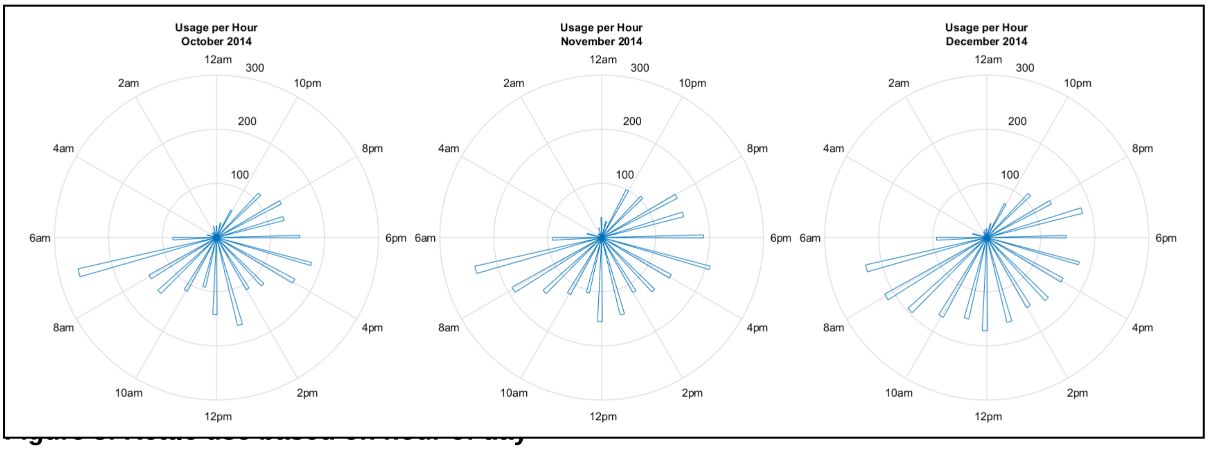
Table 2: Estimation errors for the proposed kettle model

Error	Consumption (Wh)	Water Volume (mL)	Temperature (°C)
Mean Absolute Errors (MSE)	0.086	0.025	1.210
Squared Absolute Errors	1.316	0.159	10.08

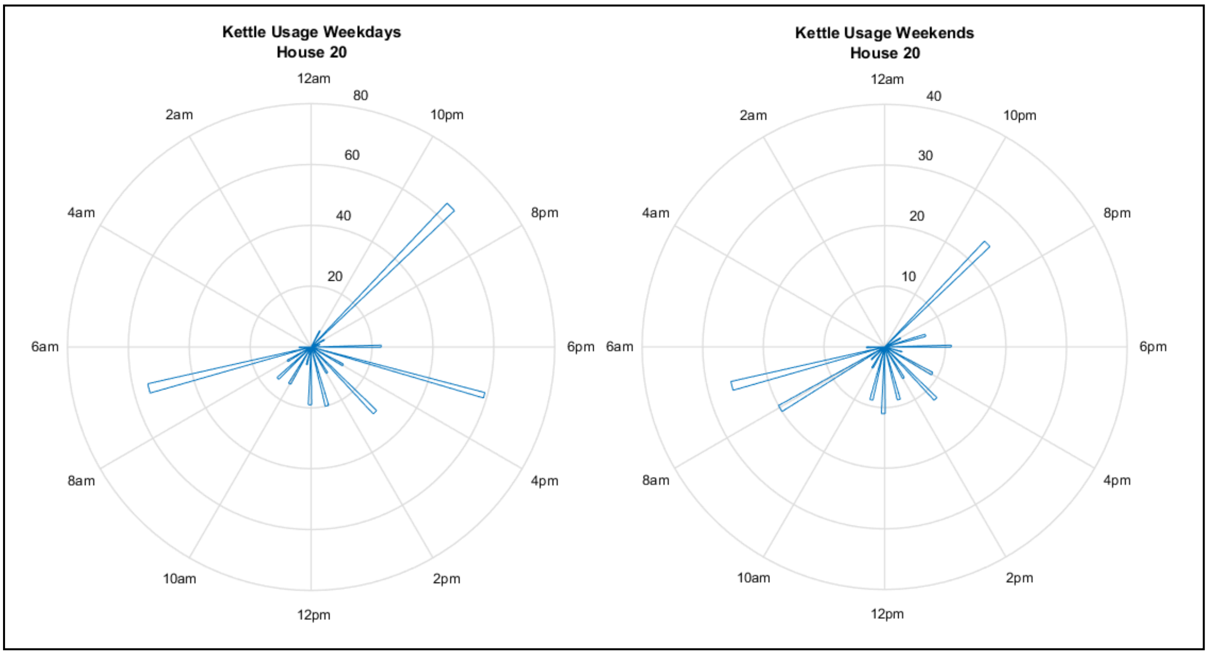
4 Usage Patterns

Our goal is to demonstrate that there are certain predictable patterns in kettle use, e.g., a high likeliness of usage in the morning. Each household monitored has its own distinct usage patterns. However, there is some similarity that can be observed. This is especially evident in households where occupants work as this dictates their schedule leading up to the workday.

Figure 3 shows results, presented as rose charts, for all 14 monitored houses for three different months during Autumn-Winter 2014. Each bar shows the number of times kettles are used in these houses during specific one-hour period. It can be seen that October and November have similar patterns with morning, lunch and 4-5pm usage peaks, attributed to the average UK working day. The usage pattern for December however shows a much more even distribution, the peaks are still apparent but much less defined. This is expected because the holidays affect the days householders are at home, or has increased likelihood of guests. We also note that the colder weather increases the uses throughout the day.

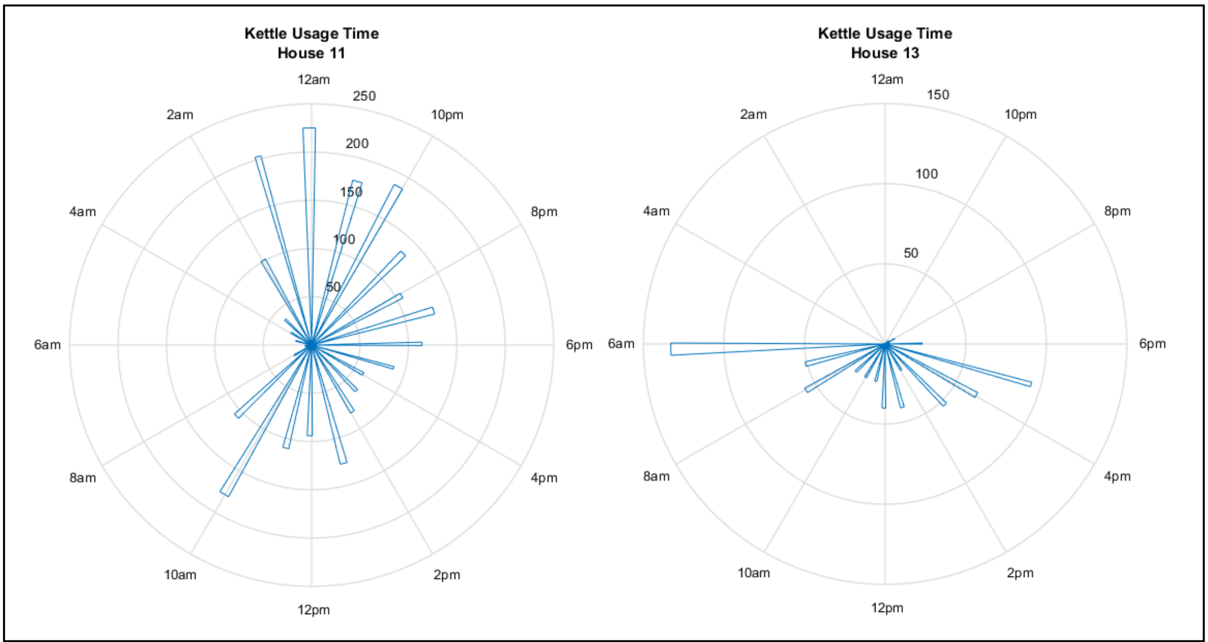


Kettle uses from 14 houses combined to show the average kettle usage pattern; a use is defined as an event lasting longer than 10 seconds.



House 20 is occupied by a family of three with one child. Data for House 20 is grouped by weekday or weekend. A use is defined as an event lasting longer than 10 seconds.

Figure 4 shows results for one particular house (House 20) for the period October 2014 - December 2014 broken down as workday and weekend. There is a striking difference between weekday and weekend usage. Weekday peaks are 7am, 5pm and 9pm peaking at the normal meal times and the house specific night time. The week has the same morning and nigh peaks but with no 5pm peak and similar usage levels throughout the day. Usage at the end of the day remains fairly consistent and may signify a regimented time for sleep. This latter observation is useful for social scientists to understand activities in the home and their energy-consequences.



House 11 (left), House 13 (right), occupied by a single retired occupant and a couple with two small children, respectively. Kettle usage over period 27 June 2014 – 20 January 2015

Figure 5 (left) shows kettle usage patterns for House 11. House 11 has the usage pattern of a 'night owl'. Indeed, usage is unusually low during the most expected hours of usage (7-9 am); instead, the usage usually starts at midday and continues over the afternoon till late with a final spike at midnight dropping of as 2am passes. The low usage throughout the, suggests that the occupants do not have a work schedule that they have to keep to. This more unusual pattern can therefore be attributed to there being a single retired occupant in the property who has a nocturnal sleeping pattern. This is confirmed by discussions with the occupant.

Figure 5 (right) shows kettle usage for House 13. House 13 has a more regular pattern in relation to today's general working lifestyle - a large peak at 6am signifies the waking time of at least one occupant and a secondary peak at 5pm signifies their return home after work. This is expected as the occupants of House 13 are a couple with two small children; hence, usage throughout the day confirms that one member works full time and the other cares for the children. Our household surveys confirm this conclusion.

The level that kettle had been filled to during operation is also studied. Each household has a clear preferred limit as shown in Figure 6 for five houses. Ideally, usage should be a large peak at the expected consumption for the number of occupants multiplied by the number of hot drinks being prepared. Patterns have emerged however, showing households with residents that tend to stay at home for longer periods of time (retirees, stay at home parents) tend to consume more per usage (fill the kettle more, boil more than needed). In some cases while the consumption is in line with the number of people in the household, there is still room for improvement and a decrease in re-boiling will help overall consumption.

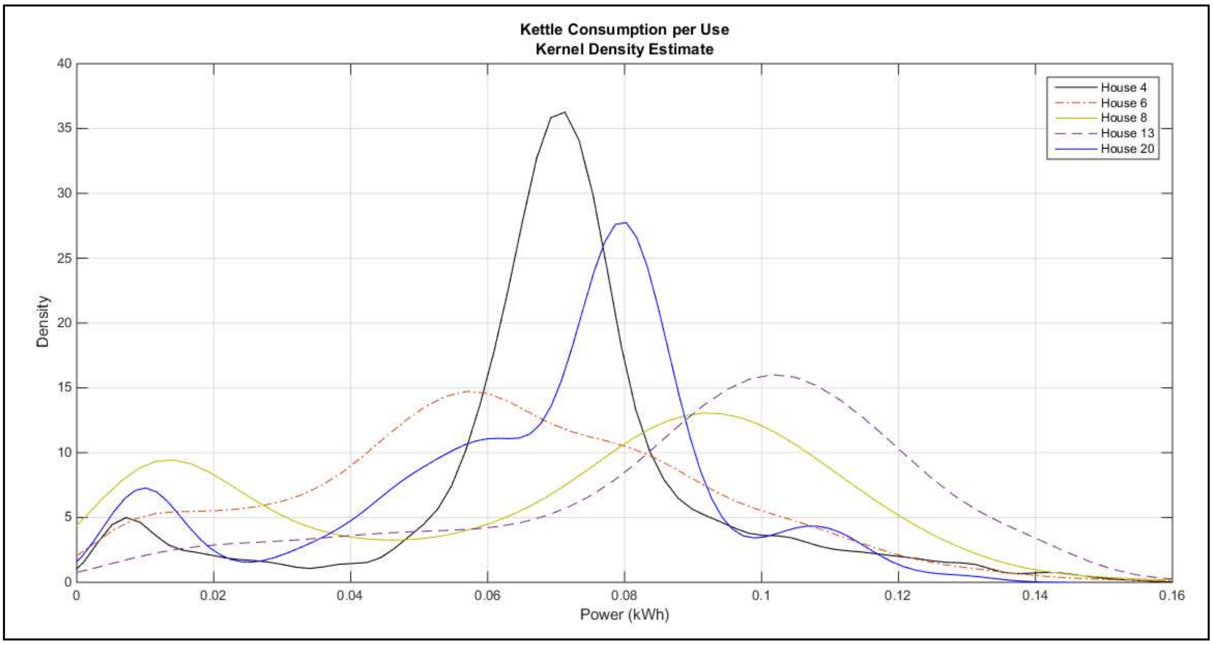


Figure 6: Kettle consumption Density per use

Figure 6 shows that different households have different levels of consumption per boil. We know from our household survey that all of these houses have standard kettles. It can be seen that House 4 (a retired couple) boils consistently at the same level with a small peak at low consumption showing re-boils. Re-boils are assumed if energy consumption is below a reference value of joules needed to heat water from 12 to 100 °C, (92109.6 Joules). It can be seen that House 6 does not have a concentrated fill pattern peaking at a slightly lower level than House 4 but remaining high across higher values as well. Houses 13 and 8 can be seen to consistently fill the kettle more but vary more than House 4. Using this data and the proposed mathematical models, the estimated fill levels for House 4 and House 8 are calculated and shown in the Figure 7.

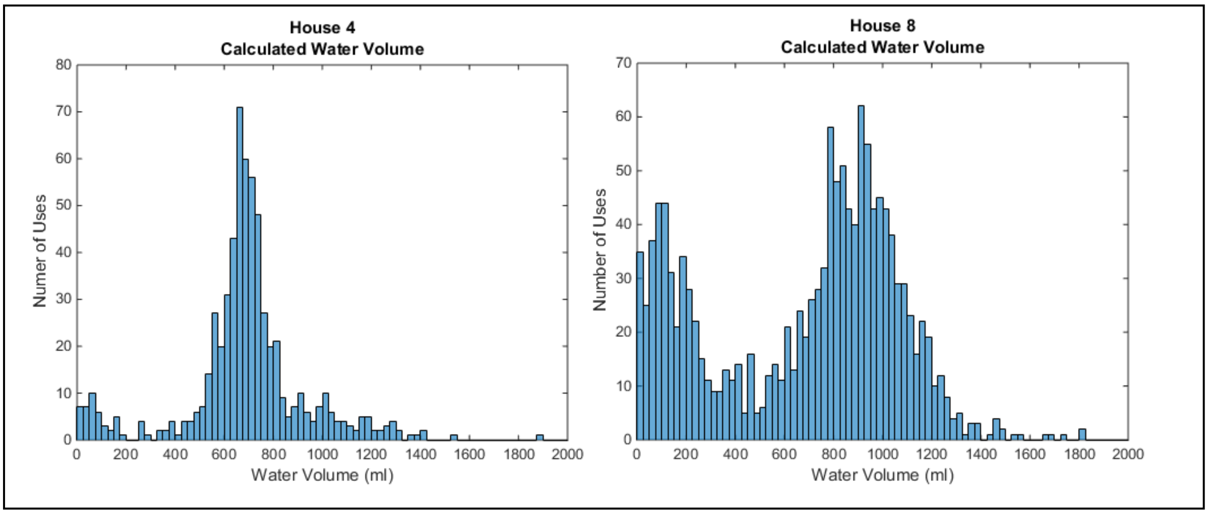


Figure 7: Estimated filled volume levels using the proposed modelling.

House 4 (left), House 8 (right) Kettle usage over period 27 June 14 – 20 January 2015.

It can be seen from Figure 7 (left) that House 4, which is occupied by a retired couple tend to fill the kettle to a suitable level with respect to the number of occupants filling in general around 600-700mL of water each time. It can be concluded that this behaviour is ecologically friendly under the assumption that there will only be two drinks being prepared for the majority of occurrences. House 8 Figure 7 (right), on the other hand, which is also occupied by a retired couple have a higher fill volume peaking at around 1L (with the assumption that one cup is roughly 250mL). This shows a less efficient usage pattern; there are also a greater number of low-level volumes which would represent re-boiling of the kettle. Reducing the amount the kettle is filled will save energy and also help in eliminating re-boils as the kettle will not have the water necessary to produce more cups of water. Feeding this information back to House 8 will help them to reconsider their usage habits, to either reinforce their current model of use or to highlight the need to reduce the amount of water added to the kettle each time.

Incidentally, the power rating of the kettle has little effect over how the kettle is normally filled: lower rated kettles which take longer per boil are filled in a similar way to higher rated kettles. It can therefore be assumed that time is not a major consideration in kettle usage for occupants.

The effect of seasons on kettle usage is something that can be visualised in Figure 8. During our study period the expected trend of increased usage as winter approaches has proved correct with an upward trend from July to December. The slight decrease in August is attributed to a number of households going on holiday.

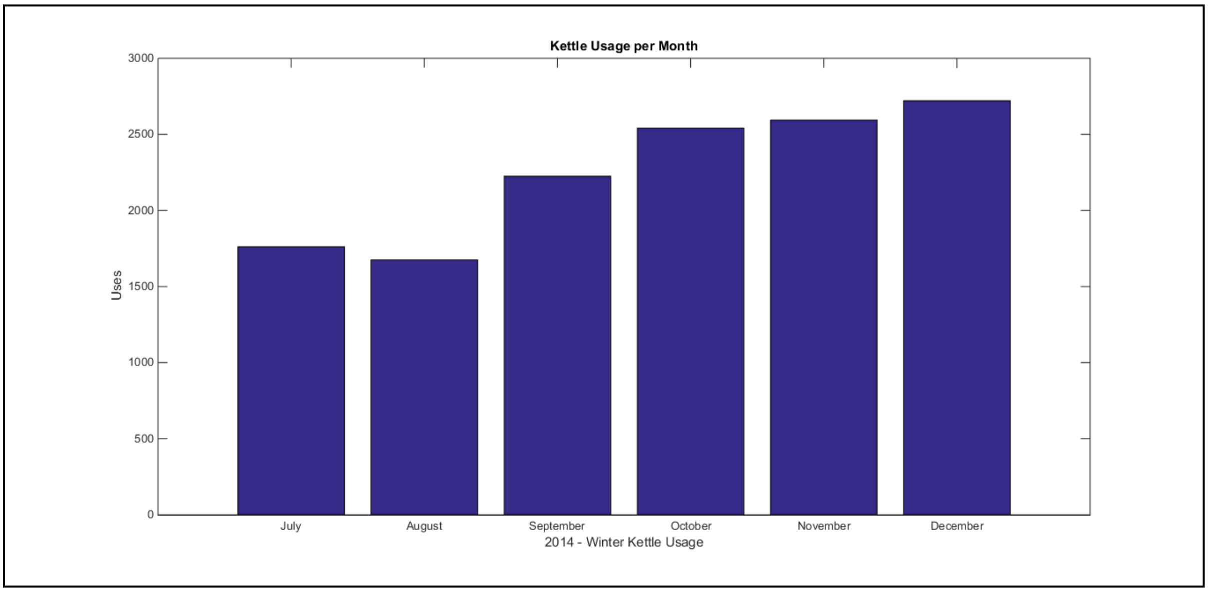


Figure 8: Kettle usage in the period July-December 2014. Kettles with full month recording from 14 houses

A major factor in consumption is the occupancy of the household. Table 3 shows the consumption for each house over the month of December 2014. It can be seen that consumption varies significantly even in households with a similar number of occupants. It can be seen that kWh per use also varies. Referring back to Figure 7 House 4 and 8, although they have different filling patterns their consumption is very similar when number of usages are taken into account. Although House 8 has a significantly higher number of uses the cost per use is similar, throughout the year the cost to house 8 remains in line with House 4 suggesting that re-boiling doesn't strongly affect consumption. Noticeably some houses have a much higher kWh per use than others. For example, Houses 9 and 12 are close to 0.1 kWh per use (a relatively high value), for House 12 this can be attributed to a fill pattern similar to House 4 (Figure 7) but with the highest peak at 1.2L, in these cases comparison with other households may help to reduce the cost to the residents.

Table 3: Consumption of households with occupancy

House	Occupancy (Under 18) R – Retired	Percentage of Total Use	kWh (Month Total)	Total Monthly Cost (14.05p/kWh)	Uses	kWh per Use
2	4 (2)	4%	17.81	£2.50	244	0.072
3	2	2%	12.52	£1.75	199	0.062
4	2 R	2%	6.94	£0.97	101	0.068
5	4 (2)	3%	19.81	£2.78	270	0.073
6	2	4%	15.31	£2.15	255	0.060
7	4 (2)	2%	9.09	£1.27	120	0.075
8	2 R	3%	16.34	£2.29	239	0.067
9	2	4%	23.94	£3.36	243	0.098
11	1	7%	11.95	£1.67	165	0.072
12	3	6%	19.09	£2.68	195	0.097
13	4 (2)	2%	5.99	£0.84	68	0.088
17	3 (1)	6%	21.03	£2.95	335	0.062
19	4 (2)	4%	9.20	£1.29	160	0.057
20	3	4%	11.94	£1.67	177	0.067

5 Case Study

During the time we have been monitoring energy usage two houses have replaced their kettle. One house opted to buy a smart kettle which featured temperature control 70-100°C and a keep warm feature, marketed as a "smart" kettle. The other household purchased an "eco" kettle which featured a thermos design style which offers a high thermal retention to in theory avoid re-boiling; the model is the Vektra referenced in Section 2 [8][9]. In the case of the eco kettle the investment was aimed at saving money - the household consists of a semi-retired couple that has made other eco-friendly additions to the house including solar panels. Our case study focuses on this household to see if the 'eco' kettle is a sensible investment.

The vacuum, eco, kettle study is useful as the household introduced this kettle as an energy saving measure during our recording period; we can therefore look at their usage before and after the change to show the advantage/disadvantage of this new kettle.

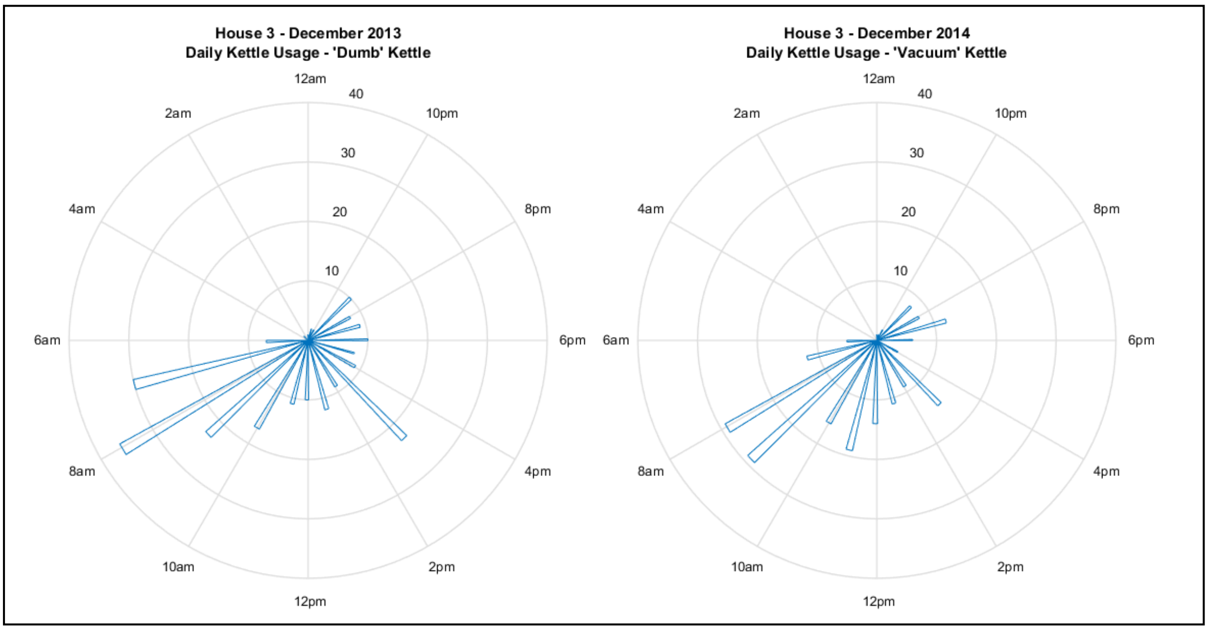


Figure 9: Hourly Usage of House 3. December 13 with 'dumb' kettle in use, December 14 with Vacuum (eco) kettle in use.

The usage pattern between 'dumb' and vacuum kettle can be seen in Figure 9. The 'dumb' kettle usage is higher than that of vacuum kettle, the hours of use have changed between years as well. The pattern helps to show the effect the vacuum kettle has had, usage is lower and the pattern shows a reduced usage after large spikes, this shows that after a use the thermal insulation reduces the number of uses for a period afterwards. This effect can best be seen at 11am usage in 2014 where the subsequent hours have a decreasing usage pattern with a spike at 3pm, 4 hours after (the vacuum kettle claims to keep water warm enough for tea for 4 hours). The average time between uses increased between 2013 -2014 by 45 minutes again suggesting that the design of the kettle is a contributing factor in the change of behaviour seen.

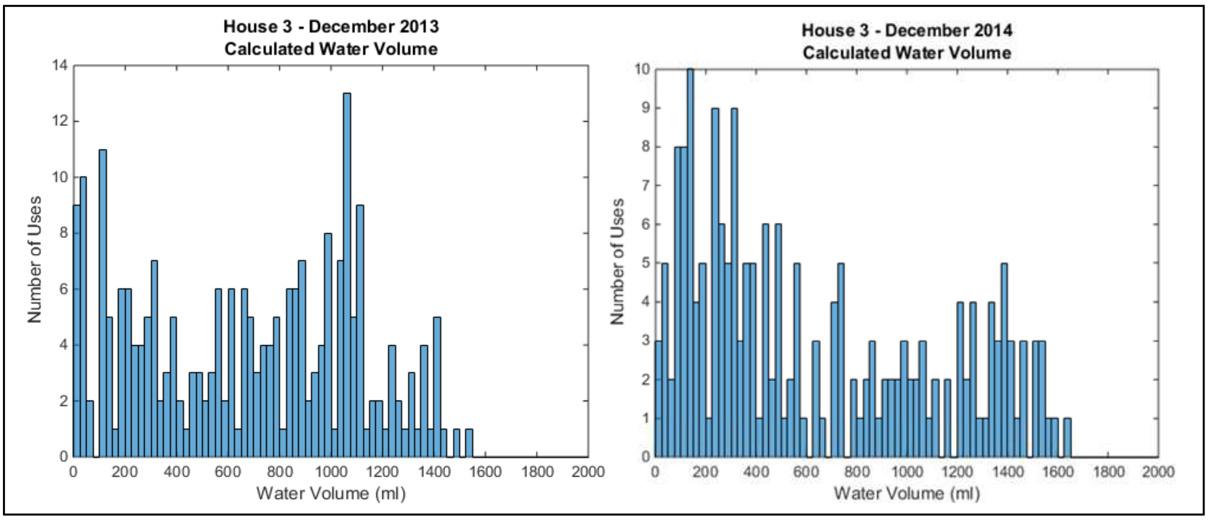


Figure 10: Consumption histogram of 'Dumb' kettle (left) vs. Vacuum kettle (right) in House 3.

It can be seen that the usage pattern of House 3 (Fig. 10) has changed since the introduction of the vacuum kettle. The vacuum kettle has fundamentally changed the way the kettle is being used in the household. In the period where the dumb kettle is in use there is a close to even spread of heating 1 litre, and re-heating 1 cup. This has radically changed during the period of use with the vacuum kettle where there is a much large proportion of small boils as well as a peak at 1.5 litre boils. We know from interviewing the household that they used the vacuum kettle by initially heating the full amount of water (capacity 1.5L) and then as the day continues reheat until requiring a complete refill. These months are a good comparison, being in the same month of the year reduces the season effect and usage was 241 and 199 for 2013 and 2014, respectively. The difference in uses can be attributed to the need to boil the vacuum kettle less. The difference in consumption can be seen from Table 4.

Table 4: 'Dumb' vs 'Eco' kettle consumption

Year	Uses	Consumption (Kilo Joules)	kWh	Cost (13.52p/kWh)
2013 – December ['dumb]	241	63,253	17.57	£2.38
2014 – December ['eco']	199	45,075	12.52	£1.69

It can be seen that the eco-kettle has a significantly fewer number of uses and therefore the associated cost has been reduced by close to £0.70 in the comparative months of December. Over the period of a year this could mean a possibility for saving around £8.00. This represents close to a 50% saving based on the figure found on CarbonFootprint.com [14]. This helps demonstrate that a desire to become more eco-friendly is possible by making little changes to appliances. The initial cost of the kettle however is around £80, therefore there is a significant period of time before the kettle will be 'saving' money.

5.1 Feedback

The residents of House 3 were given a breakdown of usage as above, along with textual explanation of the findings. A survey was completed prior to delivery of the consumption breakdown to assess the residents' thoughts. The survey revealed a number of traits about the household. The residents were committed to being eco-friendly and were positive about buying other products aimed at consumption reduction; they believed that they had changed their habits significantly as they actively inducted the vacuum kettle into their routine. As shown above, this can be seen in the comparisons made, in both usage and water consumption which led to a more economical usage style. They also made a note of the fact that they try to avoid re-heating water and this is backed by the fact that only 7% of their kettle usage is within a 5 minute window of a previous usage. Shortly after the time period included in this work the household stopped using this vacuum kettle due to a fault which once fixed never made it back into daily usage. Interestingly, this was not due to any effects on performance, but due to the noise the kettle made, which was annoying to the occupants. The feedback however was well received and the residents believed that this would be of benefit, and expressed that a monthly breakdown of appliance usage would be suitable.

6 Conclusion

This paper presents a detailed analysis of kettles usage in UK households by building a mathematical kettle model which can help analyse usage patterns and provide information about how the kettle is being used and where energy could be saved by adjusting habits. The kettle model can estimate a number of factors which would help for generating feedback. Based on the proposed kettle model, the usage patterns of households including sleeping patterns, daily schedule and interaction habits with the kettle has been studied. The studies show that, in-line with previous studies, most households do overfill their kettle. However a bigger factor is reheating water soon after it has boiled. In these cases households that appear to not overfill, based on the number of occupants, waste energy on reheating. Days of the week can affect the pattern of consumption. There is also a seasonal effect on consumption.

The case study conducted in one house, shows that there has been a fundamental change in kettle usage since the introduction of the 'eco' kettle. The household went from filling around a litre of water to filling much closer to the new kettles' maximum of 1.5 Litres which indicates the household is actively attempting to reduce their consumption. This case study also shows that the household might adjust their usage habits to meet the energy saving goals.

The analysis of kettle usage can be customized to provide feedback to individual households, assuming the households' willingness to be eco-friendly. The problem of overfilling will only be tackled by someone who is in a positive mind-set. The habit of reheating, less than 5 minutes after boiling (in 6 of the 14 houses more than 10% of boils were done within 5 minutes of the previous boil ending), is prevalent across many of the households in our study, which can be addressed by informing them that their habit of refilling/reheating is detrimental to being economical. This process of reheating could also be contributed to a lack of communication or forgetfulness: if a person is unaware the kettle has been boiled recently or has left it for a period of time there is a tendency to reheat.

Acknowledgements

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Survey of usage behavior of refrigerators, light bulbs and stand-by power in households

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Abstract

Light bulbs, refrigerators and stand-by power together represent nowadays an important amount of the electricity consumed in households. An energy efficiency program in Geneva started in 2009 promoting in households the replacement of inefficient light bulbs by efficient ones, the replacement of refrigerators older than two years by efficient ones and the installation of outlet power strips with external switch to manage stand-by power. From 2009 to 2014, more than 8000 households have participated to the program, an important part of them low income households. Close to 3000 refrigerators and more than 70'000 light bulbs have been replaced by energy efficient ones. In addition, close to 10'000 power outlet strips with external switch have been installed.

Since November 2013, most of participating households respond to a short survey concerning their behavior towards the energy usage of different appliances at home, giving additional and useful information to program evaluators. The diversity of participating households, regarding penetration of energy efficient appliances and energy related behaviors, allowed the evaluation team to analyze the spectrum of household energy consumption through a set of energy usage indicators.

After a brief description of the program and the energy savings obtained through these actions, this document presents the results of the survey and analyses the responses making comparisons with the electricity usage of those households, the inefficient light bulbs and refrigerators installed at home at the moment of the survey, and the willingness of participants to invest in energy efficiency and change behavior. As an outcome of this analysis, the energy savings potential, that the program could achieve, is estimated based on the electricity consumption and the information collected during the survey.

Introduction

A better understanding of energy usage behavior of electrical appliances in households is an important element for energy efficiency programs addressing this sector and the collection of coherent information in order to address this issue is not an easy task. The energy efficiency program "éco-social" addresses mainly low income households; since Nov. 2013, in addition to the implementation of energy saving actions, it is gathering information from households that is providing some insights about the electrical appliances and usage behavior[1]. This information is analyzed in the present study to better understand the energy usage in households and the transition to a more efficient usage that is occurring at present time. Among participating households, a broad range of energy consumption and penetration of energy efficient appliances was found. Early adopters of the new energy efficient technology can be considered as a reference and a benchmarking analysis with these households can allow for an estimation of the potential of energy savings for less efficient households.

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[1] In this paper, energy usage behavior has to be understood as owning an equipment of a given level of efficiency (for example CFL or LED light bulbs instead of incandescent or halogen bulbs) and the usage of this equipment (for example turning off lights when leaving the room).

This document is organized as follows: we describe first some pertinent details of the program to establish the framework under which the present study is carried out. Second, we give a description concerning the collection of the data that is used in the present study, namely the energy consumption of households, the characteristics of some of the electrical appliances and the information contained in the survey that is conducted in households. In section 3, we make a descriptive statistical analysis of the data obtained for the following four topics: annual electricity consumption, fridges, lighting and power strips for stand-by power. In section 4, we present the main results of the combined analysis of energy consumption and energy usage behavior. Finally using a simple linear model inspired by benchmarking, we estimate the potential savings for our sample and make a comparison with the savings obtained during previous campaigns.

1. Description of the program

The source of the information used in the present study has been obtained through an energy efficiency program carried out at present time in Geneva-Switzerland. The local utility SIG[2] (Services Industriels de Genève) for Geneva started in 2008 an energy efficiency program named éco21[3] (Jeanneret 2011, Reynaud 2014). The program is composed of a set of subprograms addressing different customer segments. One of these subprograms, named éco-social[4], is in charge of the introduction of energy efficient technologies in low-income households. To achieve this, éco-social, in collaboration with local municipalities, organizes campaigns targeting a group of buildings with a high rate of low income households in a determined geographical area.

Space heating and hot water for dwellings are provided by centralized systems for the entire building. Most of households have an electrical stove and few of them natural gas stoves. This study concerns the electricity consumption of households participating to the program.

After a period of preparation, éco-social launched its first campaign at the end of 2009 and organized the second one at the end of 2010. From 2011 to 2013, two campaigns per year were implemented and during 2014, six campaigns per year were implemented with campaigns carried out in parallel at different locations. By the end of 2014, fourteen campaigns have been implemented in collaboration with six municipalities and the participation of more than 8000 households.

Few months before each campaign, the program recruits a team, “the energy ambassadors”[5], who will visit the households that agree to participate to the program. The ambassadors are trained before the campaign during few days about energy efficiency topics by a local association in charge of the coordination and management of the campaign. In general, every campaign goes for a couple of weeks.

Few days before the campaign, intensive communication activities are deployed among the households in the targeted buildings. Those households that agree to participate arrange an appointment to receive a visit from an ambassador. During the visit, the ambassadors walk through the flat looking for energy saving opportunities, proceed to implement directly some energy saving actions and provide advice to the occupants. Among those different actions, those concerned by the present study are:

- Refrigerators: rebate vouchers are given to replace existing refrigerators/freezers older than two years by energy efficient ones of class A++ and A+++. The occupants are free to use the rebate voucher. Between 2009 and 2014, close 3000 refrigerators/freezers have been replaced by efficient ones. The rate of refrigerators that have been replaced is higher than 20%. The rebate voucher had a value of 400 Swiss Francs for some campaigns and 500 Swiss Francs for the others. This covers between 20 to 50% of the total price depending on

[2] SIG is a public owned utility providing electricity, natural gas, water and sewage for the canton of Geneva.
Website : http://www.sig-ge.ch/

[3] Website for éco21 : http://www.eco21.ch/

[4] Website for éco-social : http://www.eco21.ch/eco21/le-programme/bilan/le-bilan-eco-social.html

[5] We will call the ”energy ambassadors” just ”ambassadors” in the rest of the document.

the type of refrigerator. The sellers offered in general an additional rebate. The final amount that participants paid per refrigerator ranges from 290 to 530 Swiss Francs.

- Inefficient light bulbs: If agreed by the occupant, the inefficient bulbs (i.e. incandescent and halogen) are replaced directly by energy efficient ones (i.e. CFLs and LEDs - since January 2015, only LED bulbs are proposed in exchange). This replacement is free of charge for the participating households. Thanks to this, almost the totality of the inefficient light bulbs operating in households found by the ambassadors has been replaced. This represents more than 70'000 light bulbs between 2009 and 2014.

- Stand-by power: the ambassadors identify the outlets where electrical appliances are plugged. If agreed by the occupant, power strips with external switch are installed for IT, multimedia and other electrical equipment that present stand-by power. It is expected that these devices will help the occupants to better manage the stand-by power of the equipment plugged to them. The device and installation are free of charge for the occupants who in general agree to install the power strips with external switch. Between 2009 and 2014, close to 10'000 power strips with external switch have been installed.

- In addition of the tasks described before, since November 2013, the ambassadors proceed to make a comprehensive energy usage diagnosis using a survey form addressing the behavior habits of household occupants. This survey form helps the ambassadors to give the occupant some advices in a structured way. Based on the energy saving opportunities found by the ambassador and the agreement of a behavior change from the occupant, the ambassador provides the occupant with a quantitative estimation of potential savings in kWh and Suisse Francs per year.

The program éco21 requested in 2009 the University of Geneva to take care of its evaluation. A methodology was developed for each of the subprograms. Data collection and transfer protocols were also organized. The general methodology for the evaluation of savings and the particular methods used for éco-social were described previously (Cabrera et al. 2012). Based on the evaluation of the first eight campaigns, the savings obtained by the program are close to 380 kWh per year per household, which represent a reduction of near 15% of the electricity consumption (Cabrera at al. 2014).

2. Data collection and indicators

The data we gathered is organized in two databases, the first one concerns the annual individual electricity consumption of households and the second one the information collected by the ambassadors from the survey, their diagnosis and the replacements made. Let's note that the main purpose of the collected data has been for program management and impact evaluation purposes. Then, some hypothesis and approximations to build our energy usage indicators are made in the present study to tailor our needs. The information contained in the two databases, the data cleaning process and the construction of our energy usage indicators are described in this section here below. Unfortunately, the information concerning the size of the dwellings and number of inhabitants were not collected.

2.1 Annual Electricity consumption

The electricity consumption for the participating households is obtained from the local utility. The electrical meters are read once per year by the utility for billing purposes. The information that we obtain contains historical data with the reading dates and the amount of electricity consumed during the interval of two consecutive readings. In addition, information concerning the type of tariff, the electrical installation and the electrical meter allows us later to merge this database with the database that we obtain from the ambassadors. The interval between two reading dates is not in general the expected 365 days, but fortunately very close for most of the cases. A simple normalization is then performed by us to the raw data to obtain the equivalent of the annual electricity consumption. It happens that in some cases the interval between two readings is either too long or too short. In order to avoid errors due to seasonal effects, it has been decided to drop the data when the intervals are shorter than 330 days or longer than 400 days. The data used in this study correspond to the consumption before the implementation of the energy efficiency actions by the program.

2.2 Information from the survey – equipment's characteristics – energy usage indicators

As stated before, mainly the data concerning the fridges, lighting and stand-by power is treated in more detail in the present study. The corresponding information used for the energy usage indicators is the following:

- For refrigerators and freezers, their age is recorded under three categories: less than 2 years, between 2 and 10 years and; older than 10 years. The ambassador gets this information from the owner who in general knows when the refrigerator was bought. It is likely that for those fridges aged close to either two or ten years, their classification falls under the contiguous category, introducing some errors in the database. Eventually, for those fridges that are replaced using the voucher (this happens in general two to three months after the ambassador's visit), this information is double checked by the staff of the company in charge of removing the fridge. For households with more than one refrigerator or freezer, only the older one has been transferred digitally to the database at present time. Refrigerators represent an important part of household's electricity usage and its consumption has been decreasing the past years due to regulations and technical improvements. Also, the aging of door sealing strips tends to reduce the efficiency of a given refrigerator due to air leakage. Due to these reasons, it is expected that an older refrigerator will consume more electricity than a new one of the same size. The age category will be then used as an indicator of the amount of the energy usage for food conservation.

- The power of the replaced bulbs is registered. As almost the totality of inefficient light bulbs are replaced, the information (number and power) concerning the replaced light bulbs can be considered as a good indicator of the inefficiency of lighting devices in households and its corresponding energy usage.

- The number of power strips with external switch that are installed in each household is recorded by the ambassadors. They identify the electrical appliances plugged to the outlets, in particular those with standby power, and install a power strip if estimated necessary. As the use of an electrical appliance is in general related to the use of an electrical outlet, the number of installed power strips may be used as an indicator for the quantity of electrical appliances plugged to outlets and its electricity consumption. The number of installed power strips will be then used as an indicator of electricity usage of appliances plugged to outlets.

- The data concerning the survey contains an overall appreciation of the ambassadors about the energy usage and energy efficiency of the household during their visit. This is based on some measurements, visual observation and the responses given by the occupants who were present in the flats during the visits. Among the elements the ambassadors check, there are: the temperature inside the fridge and the freezer; presence of frost on the back wall of the freezer inside the fridge and; stand-by power management for IT, multimedia equipment and others; the ambient temperature of some rooms; position of radiator valves, etc. The number of energy usage actions considered in the survey form is 25. Ambassadors select the actions that they found pertinent and request the occupants to commit to change the behavior concerning energy usage. If the occupant agrees, the ambassador checks the corresponding case in a second form. The number of actions that the occupant agrees to commit is in general proportional to the number of actions that the ambassador found pertinent and having a significant impact of the energy usage. It is expected then to find some relationship between the committed number of actions and the energy consumption. The energy usage behavior indicator used here is based on the number of commitments made by the occupant.

Let's note that data collection and data transcription is not error free, especially when the information collected is in a paper form that is transferred to a second paper form and digitalized later. Data is not either complete. Ambassadors forget sometimes to compile all the inefficient lightbulbs, they are not able to obtain the information concerning the age of the refrigerator, etc. However, the evaluation team looked carefully for a sample and judges that errors remain small enough to guarantee that the results obtained from the analysis are accurate. The close follow up of some campaigns and the strong interaction with program managers allow us to be confident about the interpretations we are making with the data to build the energy usage indicators used in this study. In addition, the analysis made in section 4 “energy usage indicators and energy consumption” reinforces our confidence in the quality of the data.

3. Descriptive statistical analysis

Before addressing the analysis concerning the link of the characteristics of the equipment and behavior of occupants on the electricity consumption, we give in this section a descriptive statistical analysis of the different groups of data (electricity consumption, equipment characteristics and survey) in order to have a better picture of the characteristics of the sample taken in this study.

Our sample, after data cleaning, is composed of 1918 households where 496 of them were visited in October 2013 and the rest between February and March 2014 (close from 1500 additional households have been visited between June 2014 and December 2014 but the data concerning them has not yet been processed).

3.1 Annual electricity consumption

The average annual electricity consumption for our sample of households is 2390 kWh/year in 2013. As the program addresses buildings with a high rate of low income households, flats are usually smaller than the average and the average electricity consumption is also lower than the average for the canton of Geneva (2540 kWh/year per household[6]). Let’s note however that an important proportion of the households in our sample have an electricity consumption higher than the canton average. The following figure shows the distribution of the electricity consumption in 2013 for our sample (survey) and the canton of Geneva (Population).

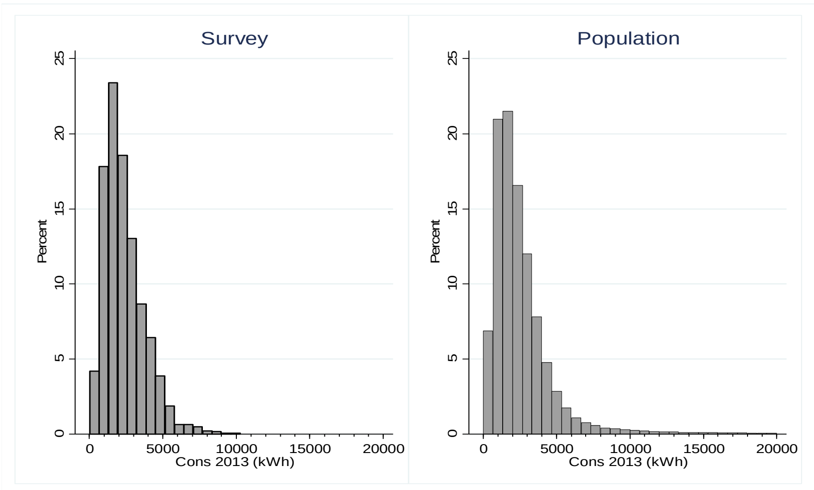

Figure 1: Distribution of the annual electricity consumption among households in our sample (left) and for the canton of Geneva (right) - only flats in buildings

3.2 Characteristics of the equipment and behavior usage from the survey

Refrigerators and freezers

The ambassadors were able to identify the range of age near 90% of refrigerators/freezers[7] in our sample. This represents 1754 refrigerators/freezers in the database. Among them, the larger

6 Only flats in buildings have been considered here.

7 Freezers are identified separately if they have their own power-supply and compressor.

proportion (52%) falls in the 2-10 years category, while 29% percent are older than 10 years and 19% are relatively new (less than two years). Let's note that a high proportion of refrigerators/freezers are relatively new in our sample. As stated before, as only one refrigerator (and possibly one freezer) per household has been registered at present time in the database, the information concerning refrigerators/freezers is not complete.

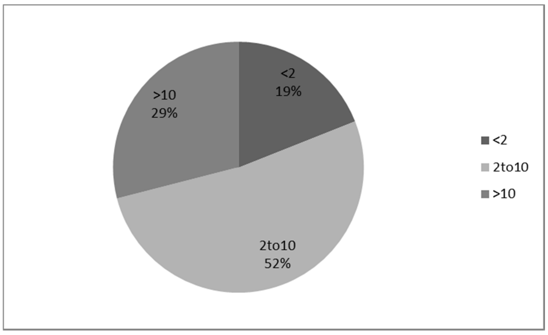

Figure 2: Distribution of refrigerators/freezers per age category

Light bulbs

There is an interesting variety of penetration regarding energy efficient lighting in our sample. Some households were already equipped almost totally with efficient light bulbs. On the other side, some households had all the light bulbs of the inefficient type. As stated before, almost the totality of the inefficient light bulbs has been replaced by the ambassadors by efficient ones. The number of inefficient bulbs discarded per household goes from zero to more than forty, with an average of 8 light bulbs per household. The following figure shows the distribution of the number of inefficient light bulbs per household (left) and the distribution of discarded power of inefficient light bulbs per household (right). Not only the power for discarded light bulbs is recorded but also for the new efficient light bulbs that replace the discarded ones.

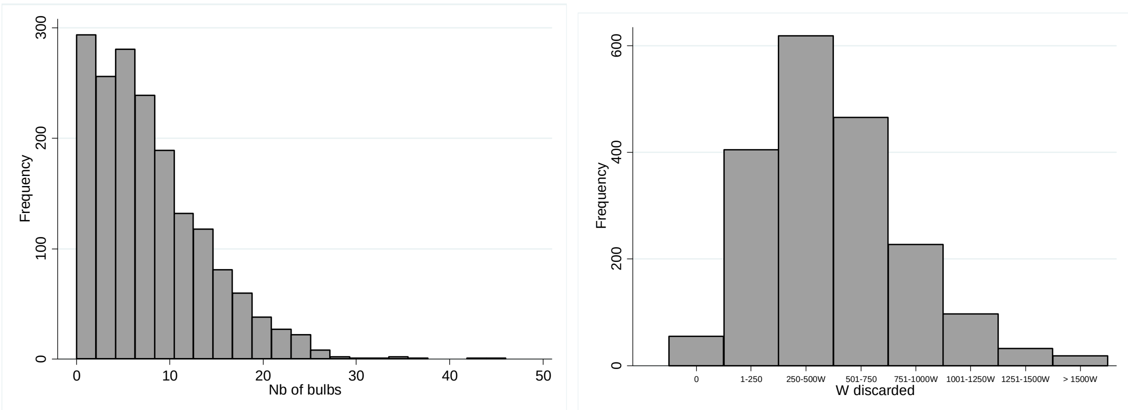

Figure 3: Distribution of the number of inefficient light bulbs per household (left) and distribution of the discarded power of inefficient lighting per household (right)

Stand-by power

With the consent of the occupant, the ambassadors install power strips with external switch in every outlet where equipment with stand-by power is plugged. The mean number of power strips installed per household in our sample is 1.1. Most of visited households (775) do not get any power strip, but in some cases they got 5 or more (15 among 1918). The following figure shows the distribution of the number of power strips installed per household. In addition to this information, the ambassador collects from the owner information concerning the stand-by management practices for four type of equipment: radio; other multimedia equipment (TV, TV box, etc.); IT equipment (computers, screen, printers, Wi-Fi, etc.) and chargers (in particular charger for cell phones that are left plugged all the time).

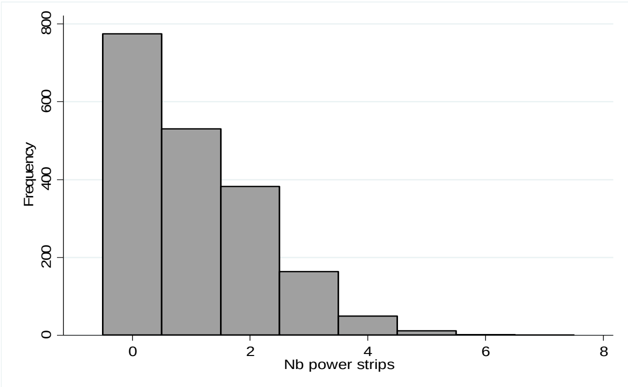

Figure 4: Distribution of the number of power strips installed per household

Usage behavior from surveys

While the three previous sections show some pertinent characteristics of the equipment installed, the present section concerns the usage behavior from the survey conducted by the ambassadors. The characteristics of the equipment are based on the observation made by the ambassador when inspecting the equipment, while the usage behavior is complemented by some measurements and the responses given by the occupant during the survey. The following figure shows the distribution of the number of actions the occupant committed to achieve. As stated before, the number of commitments are taken here as an indicator of the energy usage behavior.

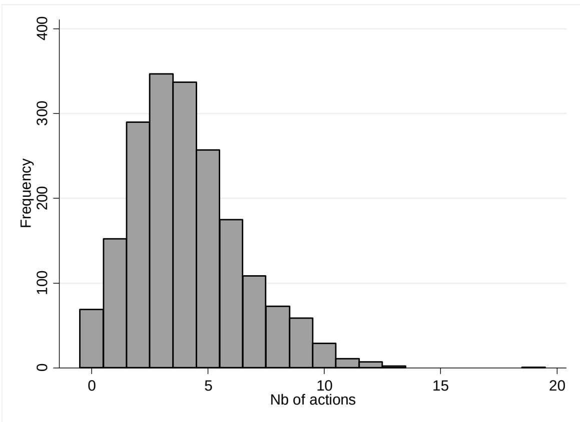

Figure 5: Distribution of the number of actions committed by household

The survey contains 25 actions. As some of them are related to space heating and heat water, which is based on fuel oil and natural gas in our sample, and as some are covered by the other indicators described previously, we keep only the no redundant actions pertaining electricity usage behavior. The following figure shows the frequencies for the selected actions used in the analysis in the following sections. Let's note that the impact on the energy consumption of the different actions, if undertaken, can be different in size.

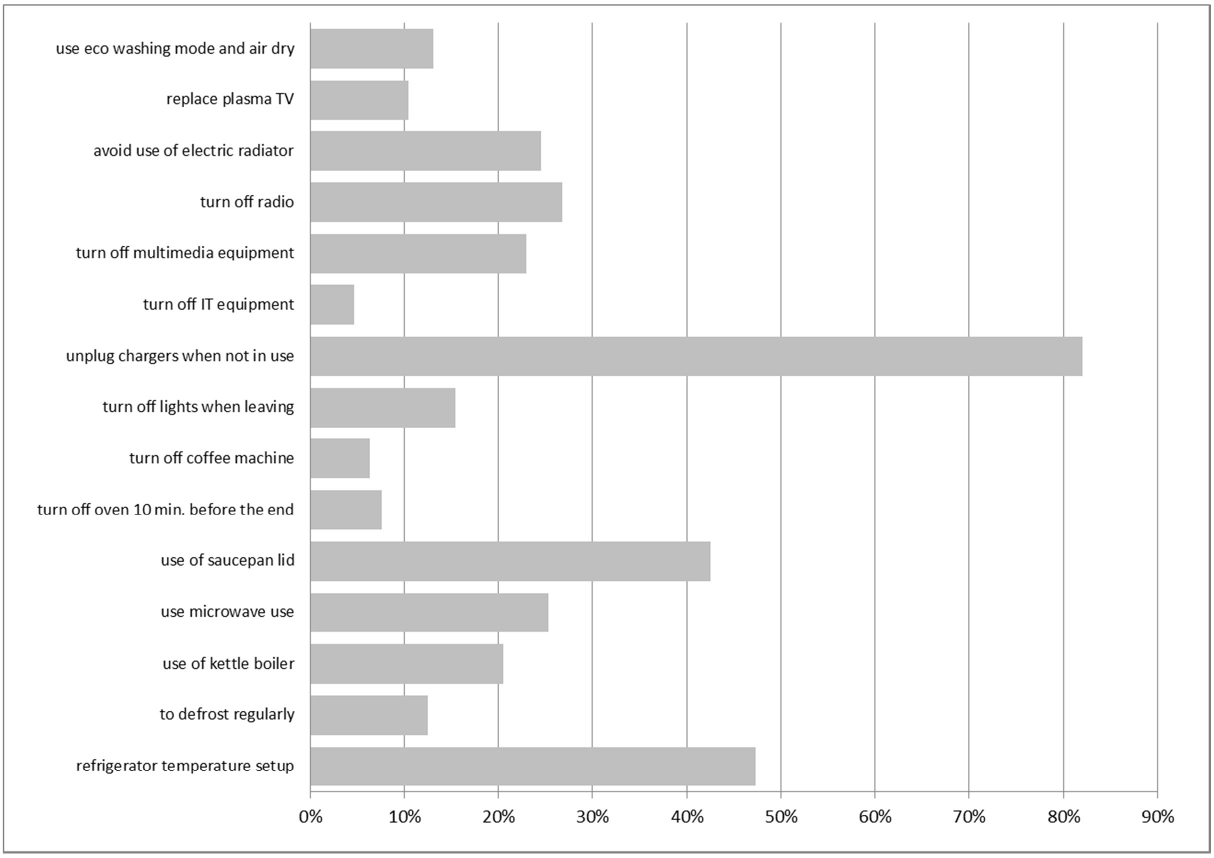

Figure 6: Frequency of the selected actions from the survey

3.4 Descriptive statistical analysis summary

Our sample shows a diversity concerning the electricity usage among households. There are households with very low electricity consumption, even lower than 1000 kWh/year, and others with an order of magnitude higher. The information collected by the ambassadors shows that, among the households they visited, there are already some of them with energy efficient appliances and good energy usage behaviors while others are completely the opposite. While the energy usage indicators cannot explain totally these differences, they have definitely an influence and this is the topic of the next section.

4 Energy usage indicators and household electricity consumption

This section attempts to highlight the link between the energy usage indicators we built in section 2 based on the information gathered by the ambassadors during their visit and the electricity consumption of the corresponding households. Let's recall here that the electricity consumption was measured before the implementation of the actions by the program.

4.1 Age of refrigerators/freezers and household electricity consumption

The following figure shows the electricity consumption of households that were grouped per age category of its older refrigerator or freezer. As expected, the mean electricity increases with age. The mean electricity consumption of households with new refrigerators is 2323 kWh/year, those with refrigerators in the category 2-10 years 2330 kWh/year and those with older refrigerators (> 10 years) 2542 kWh/year. The following figure shows a boxplot for the three categories. The difference between households with a new refrigerator and those with older than 10 years is 219 kWh/year. This value is of the order of magnitude of those that can be found in studies addressing specifically the evolution of the energy consumption of household refrigerators (IEA 4E 2014). However, the difference between households with a new refrigerator (<2 years) and those with a middle age (2-10 years), that is only 7 kWh/year, is too small from our point of view considering the continuous improvements obtained during the last years.

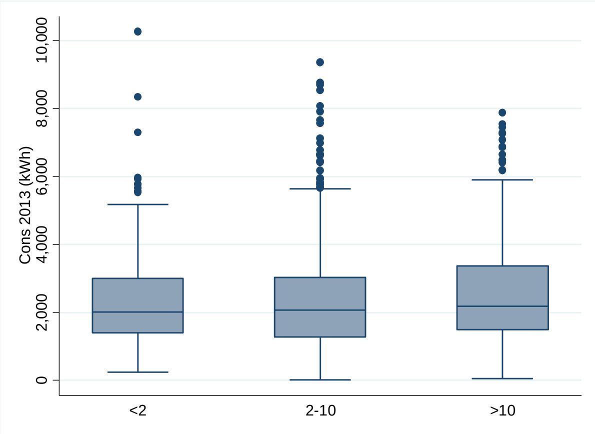

Figure 7: Boxplot of electricity consumption of households with refrigerators/freezers in one of the three categories of age (less than 2 years, between 2 and 10 years and older than 10 years)

4.2 Inefficient light bulb power and electricity consumption

The electrical power of those light bulbs that are replaced by the ambassador are registered in a power category. It is possible then to have an estimate of the total power of light bulbs removed in a given household. It can be expected for households with a higher power of inefficient light bulbs to have a higher consumption. The following figure shows the total power of discarded inefficient light bulbs against the electricity consumption of households. Households are grouped in categories of 250W. The group of households with inefficient light power >1500 W have an electricity consumption of almost 1000 kWh/year higher than the group with less than 500 W.

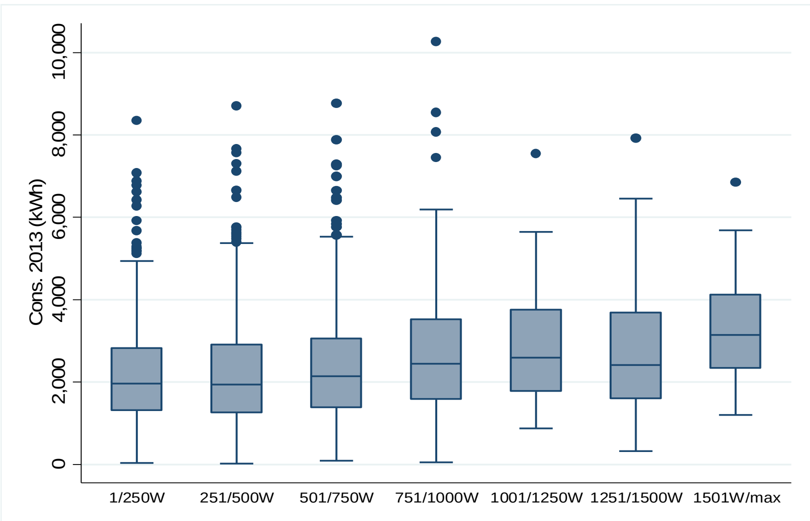

Figure 8: Boxplot of electricity consumption of households grouped according to the discarded power of inefficient lighting

4.3 Power strips – standby

As explained before, the number of power strips is linked to the number of electrical appliances plugged in the different outlets of households. The following figure shows a boxplot of the electricity consumption of households in function of the number of installed power strips. We have excluded here those households with more than 4 power strips because its number is relatively small. The correlation here is also remarkable. The difference between the group with 0 power strips and the group with 4 is higher than 1000 kWh/year.

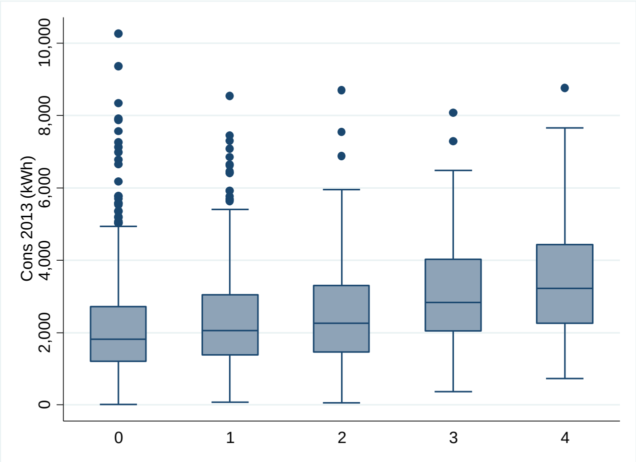

Figure 9: Boxplot of electricity consumption of households grouped according to the number of installed power strips

4.4 Commitment of energy saving actions and electricity consumption

We observe also an interesting correlation between the number of actions that the occupant committed to achieve and the electricity consumption of the corresponding household. Indeed, if the electricity consumption of a given household is high, we can expect that bad habits and/or inefficient equipment is the cause, at least partially, and this can be translated in a higher number of available energy actions to commit, information that is recorded in the survey forms by the ambassadors. The following table presents the mean electricity consumption of households in function of the number of commitments of energy savings. Despite the fact that the different actions do not have the same impact in the energy consumption, the correlation between number of commitments and energy consumption is also remarkable. Households with one commitment have median electricity consumption close to 2000 kWh/year while households with 8 commitments have more than twice.

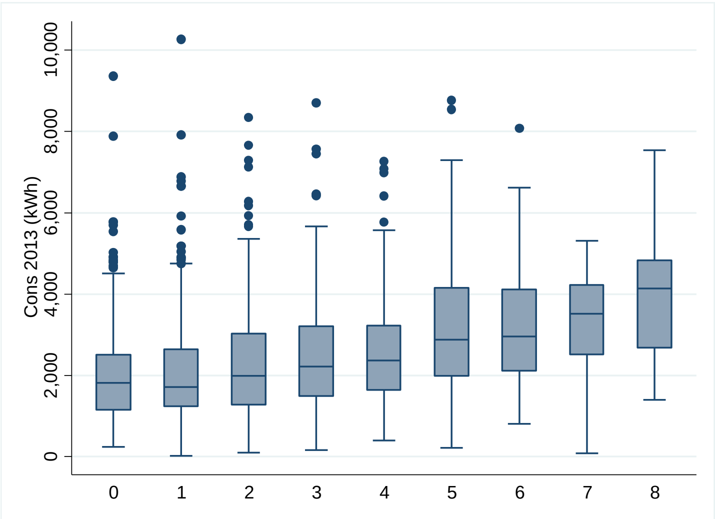

Figure 10: Boxplot of electricity consumption of households grouped according to the number of commitments

5. Estimation of the global potential savings

We define here the potential of energy savings as the expected reduction of electricity consumption induced specifically by eco-social. The results of the analysis made in the previous section increases our confidence about the data collected by the ambassadors and the pertinence of the energy usage indicators we built in section 2. It proves also that the ambassadors, although they are not trained energy professionals, collected information very accurately. Besides, Figure 1 shows that the distribution of consumptions covers a large range of electricity use intensity: the first 10% percentiles are about at 1000 kWh/y and the 90% at 4300 kWh/y. So our sample includes "thrifty and "less thrifty" consumers. This wide range can help us to estimate the savings potential for our sample if we assume that the best performers can be used as a reference. We then merge the information from the ambassadors and the electricity meter readings in order to analyze the differences in households' consumptions: we shall try to explain these differences by the "energy usage indicators" described in section 2 that here will actually represent, for some of them, energy efficiency instead of energy usage. The indicators are the following:

1. Indicator for fridge (0/1) or freezer (0/1): 1 if between 2-10 years old, 0 otherwise.
2. Indicator for fridge (0/1) or freezer (0/1): 1 if >10 years old, 0 otherwise.
3. The power saved in lighting (W removed - W replaced).
4. The number of power strips installed.
5. The number of commitments of the household.
6. Indicator (0/1) of electrical stove.

Note that the Indicators 1 and 2 (for fridge and freezer) take values between 0 to 2 : 0, if there is no fridge, nor freezer, of the corresponding age; 1, if there is one fridge or one freezer; 2, if there are one fridge and one freezer, each having its own power supply and compressor. The indicator for electrical stove (against gas stove) is introduced because the effect of this appliance on the household electrical consumption is important. As it is not directly involved in the éco-social program, it is not treated in this paper.

We introduce a simple linear model, inspired by benchmarking, which explains the differences in electricity consumption of households based on the energy usage indicators.

The linear model is: $y_i = \beta_0 + \sum_{k=1}^{6} \beta_k x_{i,k} + \epsilon_i$ (1)

where y_i is the 2013 electricity consumption of the i^{th} household; $x_{i,k}$ are the six above indicators, i.e. explanatory variables (k=1…6) for the same household, β_k are the coefficients denoting the mean impact described here below and ϵ_i is the error term of the statistical model. We recall that this model is not intended to "explain" the electricity consumption of households, but attempts to evaluate the amount of inefficient use of that electricity through a benchmarking among households in our sample.

A multiple regression is applied in order to estimate the model parameters. As the heteroskedasticity was high, we applied White correction (White 1980) to the estimated standard errors. The results are the followings:

Table 1: estimation of the β_k parameters of eq. (1)

Explanatory variable	Coef.	Std. Err.	t.	P>|t|
2-10 years old fridge or freezer	296.9	57.1	5.2	0.000
>10 years old fridge or freezer	458.5	70.7	6.5	0.000
Lighting: W removed - W installed	0.5	0.1	4.1	0.000
Nb of power strips	125.3	32.3	3.9	0.000
Nb of commitments	132.0	17.1	7.7	0.000
Electrical stove (0/1)	369.6	87.2	4.2	0.000
Constant	1011.0	112.7	9.0	0.000

All estimated coefficients are highly significant and are to be read in kWh/year except the lighting that correspond hours x10^{-3}. We should however carefully interpret these values: they are estimated from variations of annual consumptions among households that are used here to evaluate the potential of energy savings, not the real savings obtained by the program.

It is important to give some details about the interpretation of these parameters

- The two first parameters can be interpreted as the difference of the annual electricity consumption between a 2-10 year old refrigerator (respectively a >10 years old) with respect to a new (<2 years old) refrigerator.
- Concerning lighting, as the reference are the actual power of efficient bulbs, this can really be interpreted as the energy savings obtained by the program. The value of the parameter obtained (0.532) can be interpreted as the average time of use per year for light bulbs (i.e. 532 hours per year = 1.46 hours per day) that matches with our expectations and values that are found in other studies (De Almeida, 2007, Kubiak 2014). The average time multiplied by the difference of power (removed – installed) corresponds to the annual electricity savings.
- The Power strip needs to be carefully interpreted here as the differences among households are due to the existing electrical appliances that are plugged and not necessarily the difference in efficiency or usage of the same type appliances.
- The number of commitments is discussed below.
- The electrical stove has to be interpreted as the additional electricity consumption (369.6 kWh/y) for those households owning an electrical stove instead a natural gas one.
- Finally, the constant can be interpreted as the consumption of a thrifty consumer without electrical stove and with very few electrical devices.

Not only the parameters are statistically well defined, but the quantities obtained are of the expected order of magnitude.

As our sample is large, it is likely that all type of households are represented in each category of the explanatory variables. We can then we assume that the missing information concerning the size of households and number of occupants does not bias significantly our results.

Let us estimate the total potential savings for the 1918 households in our sample. The following table gives the actual total consumption in first row; the four following rows contain the energy efficiency indicator that will give the potential of energy savings. As said just above, the parameter of power-strip combines the estimated consumption of multiple devices in the household including during the stand-by mode. Only the latter can be saved under the program, but its share is unknown. Hence we do not include the power-strip estimation in the total potential, albeit a part of it should be added. For each one of the indicators, we recall the unit, the total amount of units, the mean of the estimation of energy savings potential (as given in the previous table) and finally, the total amount potential savings in kWh/year (this last column being the multiplication of the number of units by the mean savings). The potential of saving is very important (-36%).

Table 2: Estimated potential saving for the whole sample (1918 households)

	Description of units	Nb of units		Mean consumption (+) or savings (-) per unit	Total	Difference with respect to 2013 consumption
					(kWh/y)	%
2013 Consumption	Households	1'918	(+)	2'386	**4'576'597**	
Potential savings						
Fridge/Freezer 2-10 years	Nb of fridges/freezer	1'151	(-)	296.9	-341'722	-7.5%
Fridge/Freezer >10 years	Nb of fridges/freezer	634	(-)	458.5	-290'693	-6.4%
Lighting	W removed - W replaced	721'185	(-)	0.530	-382'035	-8.3%
Nb of commitments		4'859	(-)	132.0	-641'616	-14.0%
Total potential savings			(-)		**-1'656'066**	**-36.2%**
Power strip	Nb distributed	2'068	(-)	125.3	-259'218	-5.7%
Simulated 2013 consumption including potential savings	kWh		(+)		**2'920'531**	

As stated before, the above table estimates the potential energy savings and not the real ones. For example, the ambassadors identified 1151+634=1785 fridges/freezers that could be removed. In reality, 426 new fridges were installed (24%). However, for lighting, we can expect that real savings are very close from the estimated potential since practically all the inefficient light bulbs are replaced by the ambassadors. It is interesting to note here that light bulbs, despite the current policies addressing this sector since 2009, still represent an important part of the potential savings.

Another important question pertains the parameter “Nb of commitments” that is closely related to behavior: 39% of the total savings are based on the commitment of the households to modify some of their behaviors. We must critically address the question of the realization of this potential. The concern is the capacity of households to change their behavior to diminish significantly their electricity consumption. The potential saving for lighting, fridges, freezers and power strips are based on new appliances given, or bought and partially financed (fridge/freezer) by the utility; then, apart from rebound effect, there is no doubt that decrease in electricity consumption will take place. Pertaining behaviour change, we are convinced that the commitment will not fulfil the estimated potential (0.6 GWh/year, -14% of the total 2013 consumption). Our previous researches and the literature emphasize that the effects of programs oriented to promote household energy efficient behaviour are small. Bertholet et alii (2014) found a 3% of saving for another program launched by the Geneva utility[8]. Delmas et al. (2013) performed a meta-analysis of 156 published trials including 525'479 subjects, from 1975 to 2012 and concluded: “*A savings effect of 1.99% is found for high quality studies that include statistical controls such as weather, demographics, and – most importantly – a control group. In contrast, lower quality studies without such statistical controls find a savings effect of 9.57%*”. Why is there such a discrepancy between potential and realized savings in behaviour programs? We find many assumptions in the literature about the determinant of energy saving behaviour. According to Mizobuchi (2013) financial rewards are important and the effect of additional non-financial information is not conclusive. Brounen (2013) discovered that only 56% of his respondents are aware of their monthly charges of gas or electricity[9]. Many authors investigate the barriers to the implementation of new behaviours. They found that the "there was a strong association between environmental attitudes and environmental behaviours", Gadenne et al (2013). “A variety of constraints … can function as barriers to action and thus shape behaviour” Stern (1999). These constraints are constituted by the context of the households (kitchen room already equipped by owners, availability of natural lighting, etc.). Frederiks et alii (2015) give eleven psychological factors that refrain behaviour change: “it is clear that what people say and what they do are sometimes very different things”. Linden et al. (2006) write "that it is important to promote behaviours in line with recent trends in lifestyles.

The impact evaluation of the first eight campaigns (2009 to 2013) of éco-social gave savings close to 380 kWh/year per household, representing near 15% of the electricity consumption. As the actions carried out by the program for the sample (campaigns 8 to 11) used in the present study are very similar to the previous ones, we can expect that the savings will be of the same order of magnitude. Compared to the potential that we found here, the real savings obtained by the program are close to 40% that, from our point of view, is a great accomplishment.

7. Summary and Conclusions

The analyses presented in this document show the utility that data gathered from households can have to better understand electricity usage and estimate the potential of energy savings when the heterogeneity of households regarding energy efficiency is large enough and the data collected is sufficiently accurate. We combined quantitative data (meter readings) and qualitative ones collected by ambassadors (not professional in the energy field). The training they received during few days prior the program campaigns, allowed them to have the necessary background to collect the pertinent information regarding energy usage.

The current energy efficiency policies introduced by the Swiss Government, for example the application of the European directive 2009/244/CE (ban of incandescent bulbs since 2009), led a group of households to become more energy efficient while others stayed yet relatively inefficient. This transition allows having at present time a wide range of efficiency among households. Based on this heterogeneity, a simple statistical model estimates the upper bond of the potential of energy savings for our sample. However, this potential overstates the true savings potential because we are

[8] The program Doubléco was addressing the small customers (mainly households but also small companies). The participants committed themselves to reduce their electricity consumption for which they were rewarded with a monetary incentive; it took the form of a rebate on their bill: 44'400 households participated to that program.

[9] In Brounen's sample, space heating charges are included in the bills. As no heating is included in our survey, we suspect that our rate is definitely lower.

not able to distinguish efficiency from usage for some devices, and because the behavior change is difficult to implement and to maintain in the long time.

Light bulbs still represent an important part of the potential savings (-8.3% of household consumption) despite the fact that policies are aggressively addressing this sector, Cabrera et alii (2015). The program éco-social is exploiting almost the total potential of this segment and accelerates dramatically the evolution of households' equipment towards optimal efficiency.

Financial support of the program helps to renew the park of refrigerators and freezers: 21% of the 2-10 years old fridges and 29% of more than 10 years were replaced three months after the ambassadors' visit.

The power strips (2068) were distributed and the economy induced by the suppression of stand-by is not estimated very accurately, further studies are necessary to determine the savings more precisely.

A large number of commitments (4858) were harvested by the ambassadors. Behavior presents an important potential for energy savings but we suspect that they will hardly carry on. Let us note that technological improvement of electrical appliances will reduce the impact of behavior change (i.e. turn off the light when leaving the room will save less energy if a LED bulb is installed instead of an incandescent one).

Based on previous campaigns, the total real savings accomplished by the program are close to 40% of the potential savings estimated in this study.

Acknowledgements

We would like to express our gratitude to the program éco21 and éco-social to trust the University of Geneva for the evaluation of their program. We would like also to thank the utility SIG for the data provided concerning the electricity bills. Thanks to the reviewers who suggested very interesting references. Finally, we would like also to thanks the ambassadors who filled in the forms with valuable information for the evaluators and the organization Terragir in charge of the training of the ambassadors.

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Assisting user airing behavior for saving energy

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Abstract

The focus of our paper is the question of how we can influence user behavior in private households in order to achieve a higher level of energy efficiency for space heating. We used indoor air CO_2 concentration as an indicator for ventilation behavior. To do this we monitored indoor air quality (CO_2 concentration, temperature, air pressure and relative humidity) and logged the data. The current state of ventilation (windows open, closed etc.) was recorded using window/door sensors with rf-communication.

The homes are equipped with devices to monitor the air quality and to assist the residents in airing. The current CO_2 level is indicated by an LED light bar. Additionally, the device shows the current value for temperature and humidity. The residents are informed of when the right time to open the window and then when to close it again to reduce the loss of heating energy.

The dew point temperature of indoor air was also calculated to see if there are critical values for the dew point to prevent mold formation. At the same time we recorded the current heat energy consumption.

For one week, indoor air quality and user behavior were monitored without any assistance devices to discover if there is a difference in energy consumption. Surprisingly, we found out that about 77% of the households have achieved heating energy savings when using the assistant device for monitoring the indoor air quality. The mean and peak values of the reductions were recorded at 1.4% and 31%, respectively

Introduction

Expenditure for heating energy in private households related to square meter in Germany in the last 20 years is continuously growing as shown in Figure 1. With this growth the significance of energy loss through ventilation is getting more important. To find out how big the saving potential is in this field, we carried out measurements in private households.

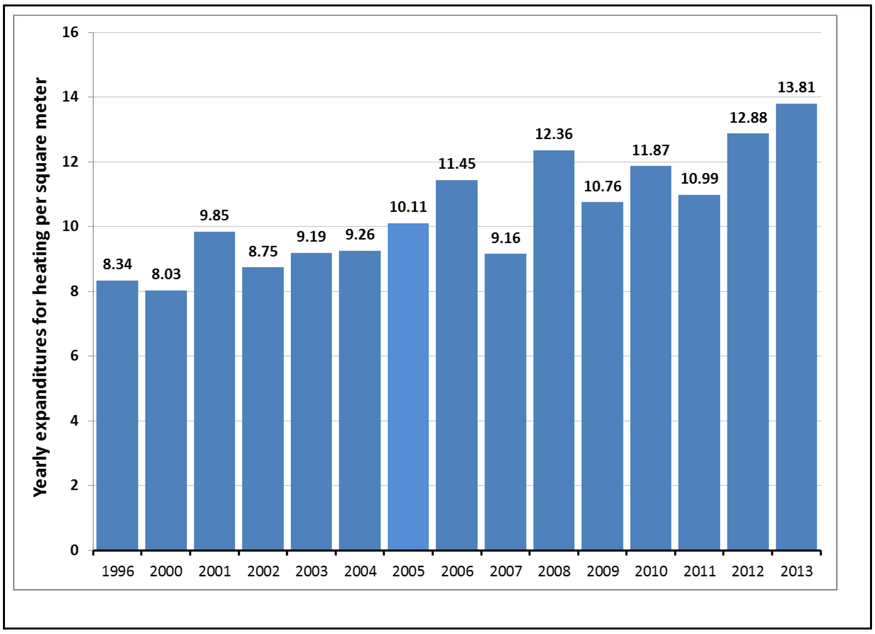

Figure 1: Yearly expenditures of private households for heating[1] in Germany from 1996 until 2013 (in Euro per square meter) [2]

Many research reports from different countries have discussed CO_2 concentration of indoor air and its influence on human health and work productivity [8], [9], [10].

The difficulty of balancing the right airing time with indoor air quality and t thermal comfort[2] during winter is a well-known problem. On the one hand, it can be unhealthy to breathe in air that has been circulation in one room over long period of time [1] and on the other hand a too long airing period is not energy efficient. Long window opening time determines higher consumption of heating energy to replace the sinking indoor air temperature which means heat energy losses. The question we wanted to answer is how we can combine these two influence factors and does higher indoor air quality mean higher energy consumption. The human nose is not the correct sensor for the measurement of CO_2 and accompanying gases. The human nose adapts over time and does not give an alarm about high concentrations of polluting gases in the air. To highlight the change in air quality there should be an assistant device

We will establish the following preliminary hypotheses concerning indoor air quality in the monitored households:

- When we observe the airing behavior of the participants and give them feedback about their behavior, this will affect the user behavior:
- After receiving feedback about their behavior the indoor air quality will improve (CO2-content, relative humidity)
- The airing period will be reduced using feedback to the user
- As determined in the field test the year before [3], the efficient airing behavior of the tenant is decisive for the heat energy consumption and not only the indoor air temperature.
- Short airing periods are more efficient and ensure the sufficient volume of fresh air and extraction of air humidity. The resultant heat energy loss is insignificant.

[1] Heating energy for hot water and space heating.

[2] Thermal comfort is the condition of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation [12]

- On average, the households with automatic temperature control have a lower indoor air temperature than households without automation [3].
- There is no strong correlation between room temperature and energy consumption [3]
- Participants living in older buildings have nearly the same room temperatures in their living rooms as participants in newer buildings. [3].

Field Testing

An online survey was launched to collect household data such as building attributes (year of construction, wall construction type, standard of thermal insulation) and yearly energy consumption. Roughly 40 different households were willing to participate in the field testing measurements. Among them there were 32 households (dwellings in multifamily houses and detached houses) that received the home automation system for single room heating control. In four of the households it was not possible to capture the heat energy consumption data. Ten households each received one LUQA IAQ monitor and it was placed in the living room. The monitor gave the user feedback about the indoor air quality and at the same time recorded data.

Measuring equipment: Testo IAQ logger

Indoor air quality measurements could be done using a mobile sensing device with a sensor probe containing a CO_2 sensor, a temperature sensor and a relative humidity sensor. Data logging was possible on an internal storage device. The measurement rate was every 3 minutes with infrared gas sensors (NDIR). A nondispersive infrared sensor (or NDIR sensor) is a simple spectroscopic sensor often used as a gas detector. It is nondispersive in the sense of optical dispersion since the infrared energy is allowed to pass through the atmospheric sampling chamber without deformation [7].

Figure 2: Indoor air quality monitor LUQA[3], Testo IAQ logger[4]

LUQA indoor air quality (IAQ) Monitor

This piece of equipment has a log function for the internal long-term recording and a USB interface including analysis software with charts (picture). It has been designed to monitor temperature, humidity, and CO2 levels as well as volatile organic compounds (VOC) in indoor air. LUQA IAQ monitor has an internal storage device for logging data for two weeks in one minute step. LUQA indoor air quality monitor has three light colours for signalling following three CO_2-concentration levels:

Green LED CO_2 concentration < 1000 ppm good air quality and no action needed

[3] http://www.elk.de

[4] http://testo.de

Yellow LED   1000 ppm < CO_2 concentration < 1500 ppm   acceptable air quality

Red LED CO_2 concentration > 1500 ppm   bad air quality   airing will be recommended

Figure 3: RWE Smart Home system5

Home automation system for single room heating control

A simple home automation system for adjusting the indoor air temperature in each room consists of three parts. These three parts consist of: a gateway for the connection between the components, connection via internet with the server for data logging, wireless radio thermostats and door/window-sensors. The window/door sensor is a product consisting of two elements. One element is mounted on the moving part of the window or door. The second element is placed on the frame and contains two alkaline 1.5 V batteries. If an action is detected, the sensor sends data as a signal to the radio frequency network main controller.

Wireless radiator theromstats are mounted on the heater valves and control the vales by a motor. The motor needs three 1.5V alkaline batteries that should last two years. When the tenant opens the window for ventilation, the heating control system automatically switches the radiators off to minimize energy consumption and when the tenant closes the window, the heating control system starts up again.

The RWE Smart Home graphical user interface (GUI) was used for configuration and control of the devices and heating profiles of the individual rooms and for each day of the week.
Smart phones/tablets/ Android/IOS Applications could only be used for remote control of the devices.

For one week the measurement of the status quo was carried out. Here data was logged of indoor air temperature, CO_2-content, and relative humidity once every three minutes in three rooms of one household (mostly living room, bedroom and bathroom). For this purpose logging devices were assigned. At the start of the measurement, the heat energy consumption gas meter readings and timestamp were recorded. Also at the end of the measurement heat energy consumption readings and time stamp were recorded. Sensor installation height, room type, floor area, room height, heaters (type, valve type), heating system data (type, year of construction, settings, nominal power), and room attributes were also recorded.

The data base for data storage that was designed for loggings of sensor data for indoor air was designed. Logged data were transferred to the data base (CO_2 content, indoor air temperature, air pressure, relative humidity). Further values were calculated (saturated steam pressure, absolute humidity, dew point temperature, steam pressure) and weather data from the city of Bottrop (outdoor air temperature, wind speed and direction, solar radiation) used for calculation of the heat energy consumption were recorded. Using a MatLab[6] database toolbox to create a connection to the

[5] http://www.rwe-smarthome.de

[6] Mathworks

database heat maps were generated, along with scatterplots and density plots. Heat energy consumption was calculated using a simple solution approach to compare the weather adjusted energy consumption over two weeks.

Evaluation

Measurements with LUQA IAQ monitor

The following conclusion was reached regarding the CO_2 concentration of the indoor air on average evaluated divided in the first week of measurement (status quo week) and the second week using home automation or LUQA IAQ monitor The improvement was detectable in most households which used a LUQA monitor.

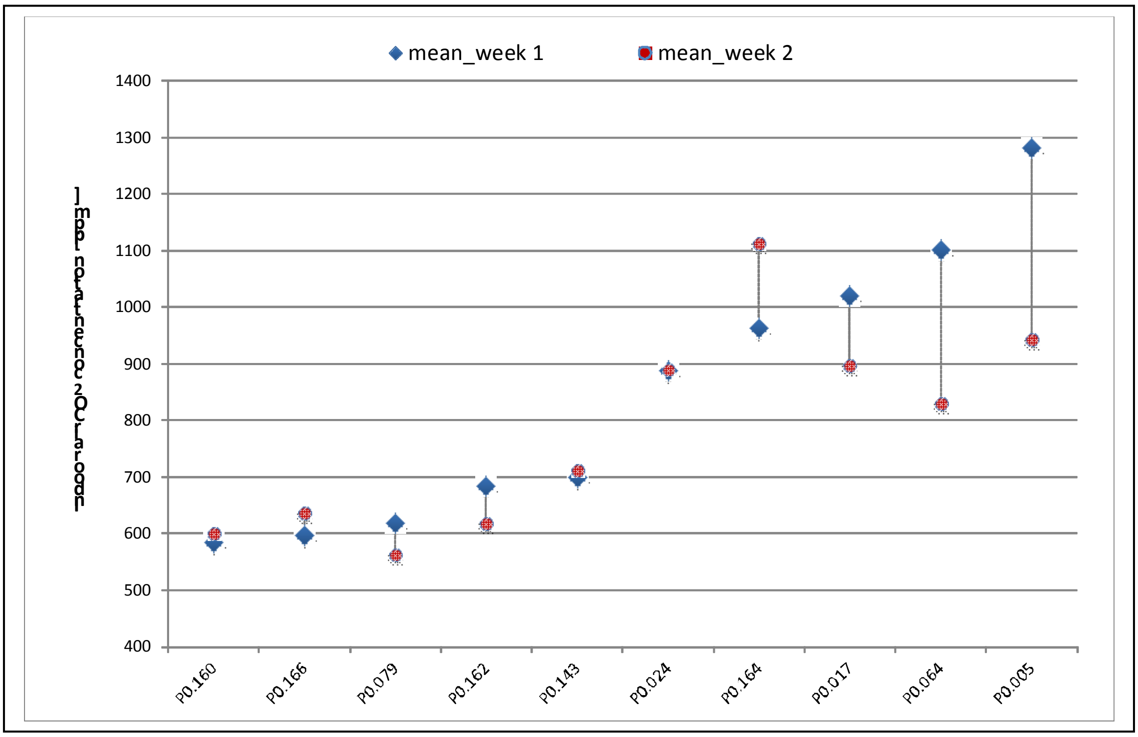

Figure 4: Mean CO_2 concentration in the week 1 (without LUQA monitor) and week 2 (using LUQA monitor) in the living rooms of the households

Due to the mean CO_2 concentration (Figure 4), the households which could use a LUQA IAQ monitor have shown (as accepted) a more frequent higher indoor air quality (lower CO_2 concentration) in the second week. Therefore we can identify two groups of indoor air quality: the first group of participants with, on average, a rather low CO_2-concentration (<800 ppm) and the other group with, on average, a rather high CO_2-concentration (>900 ppm). While the households group with low CO_2-concentration of indoor air did not change very much during the second week, the group of households with higher CO_2-concentration experienced remarkable changes in the second week. Four out of five households with high CO_2-concentration lowered the indoor air quality with about 120 to 330 ppm on average.

In the household P0.164 the indoor air quality worsened in the second week (Figure 13) and reached energy savings (Figure 7). Using the LUQA device the participant obviously decided that the indoor air quality range from 1000 to 1500 ppm sufficed and his behaviour according to this decision resulted in energy savings. Even if the air quality was not better than in the week without the assisting device, it was still reasonable.

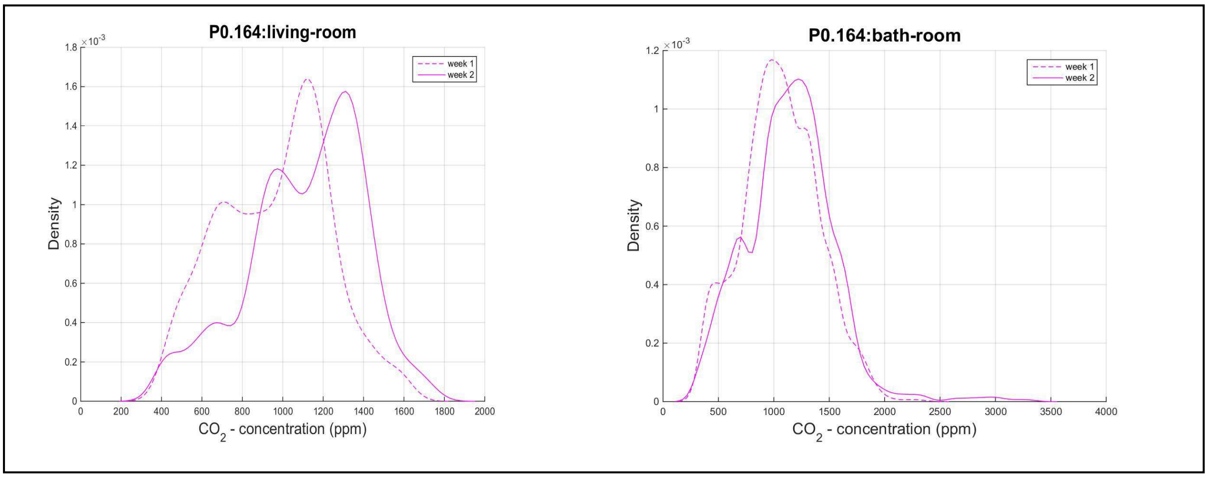

Figure 5: Density of CO2 concentration in week 1 (without assistance) and week 2 (using LUQA monitor) in the living room of the participant P0.164

In Figure 5 the shifting of CO_2 concentration from lower in week 1 to the higher level in week 2 is visible. This is understandable because the air quality was relatively good in week 1 and the slight reduction of airing periods with the assistance of the IAQ Monitor was therefore possible without annulling the existing high level of indoor air quality. Energy savings in week two compared with week one was about 5 %.

In the following chart (Figure 6) is a so- called bubble diagram, which shows three variables of indoor air quality (CO_2-concentration, temperature and relative humidity)as an average value for four daytime periods (four colors). It also includes a comfort range (Behaglichkeitsfeld) according to DIN EN 15251 - a German technical guideline. This field describes the comfort preferences of majority of test persons concerning indoor air temperature and odorous substances depending on relative humidity.

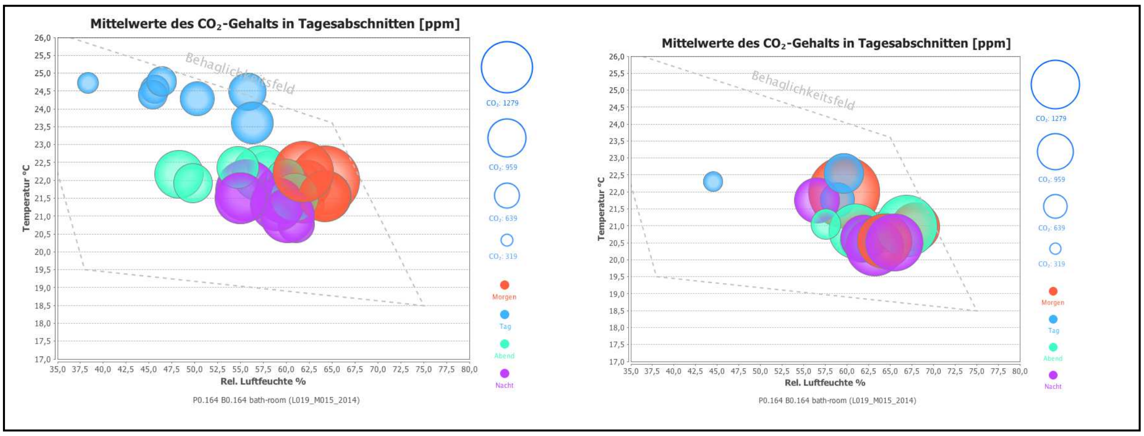

Figure 6: "Bubble" diagram for the week 1 (without assistance) and week 2 (using LUQA monitor) in the bathroom of the participant P0.164

Here it can be seen that the temperature level in the second week sank over the day. Relative humidity rose slightly during the night and the CO_2 concentration stayed the same (diameter of the circle is corresponding to the CO_2 concentration).

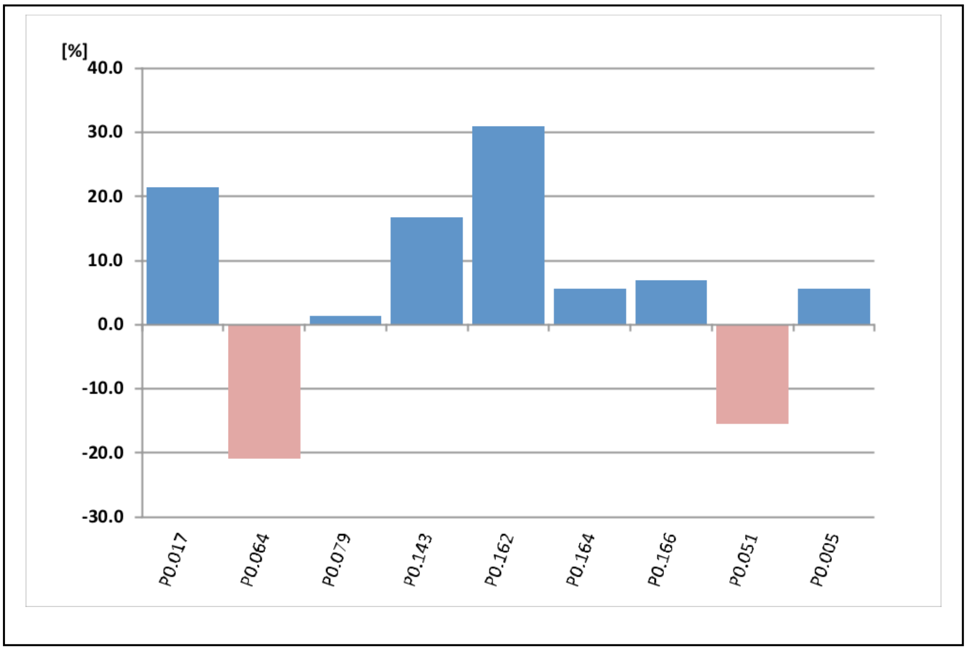

Figure 7: Comparison of the calculated heat energy consumption in week 1 (without assistance) and week 2 (using LUQA IAQ monitor)

Furthermore there was a noticeable effect on energy savings as regards heat energy. As shown in Figure 7, about 77% of households have achieved a considerable saving potential in the week with airing assistance (blue bars). Two households have used more heating energy in the week when they used IAQ assistance device. Indoor air quality changed significantly - caused by more ventilation periods in the second week (P0.064). This can be detected in the temperature heat map (upper chart) in yellow and blue strips. Even if the indoor air quality in the first week was relatively good, the high amount of airing periods lead to almost continuously low CO2-concentration.

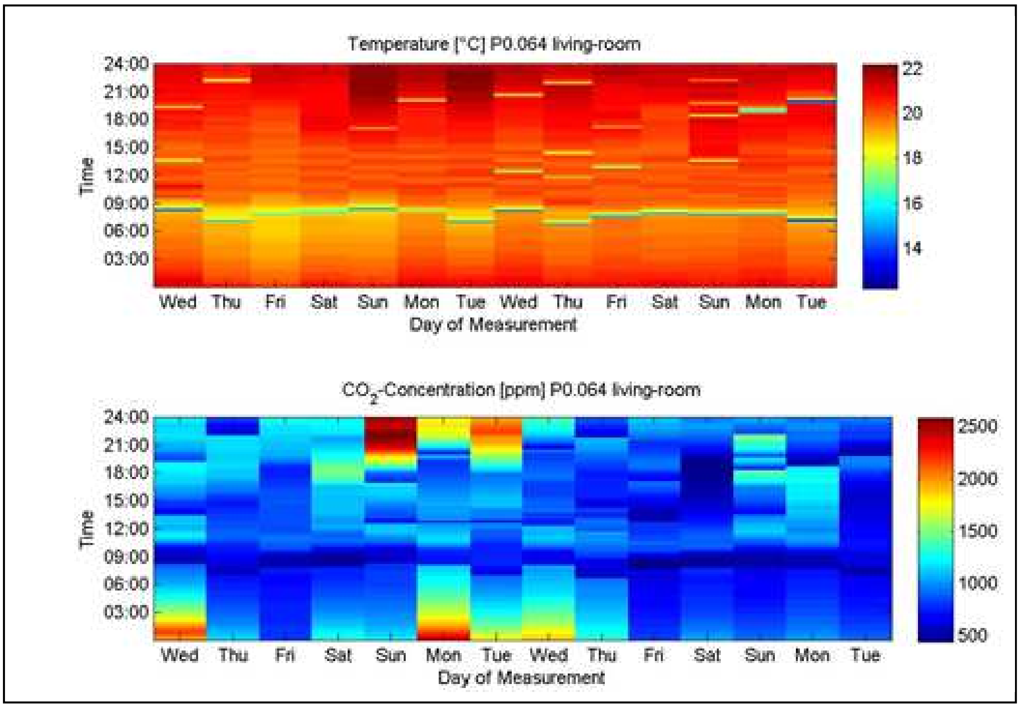

Figure 8: Heat map of indoor air temperature and CO2 concentration over two weeks (first week without any system and the second week with LUQA monitor and home automation system) in the living room, P0.064

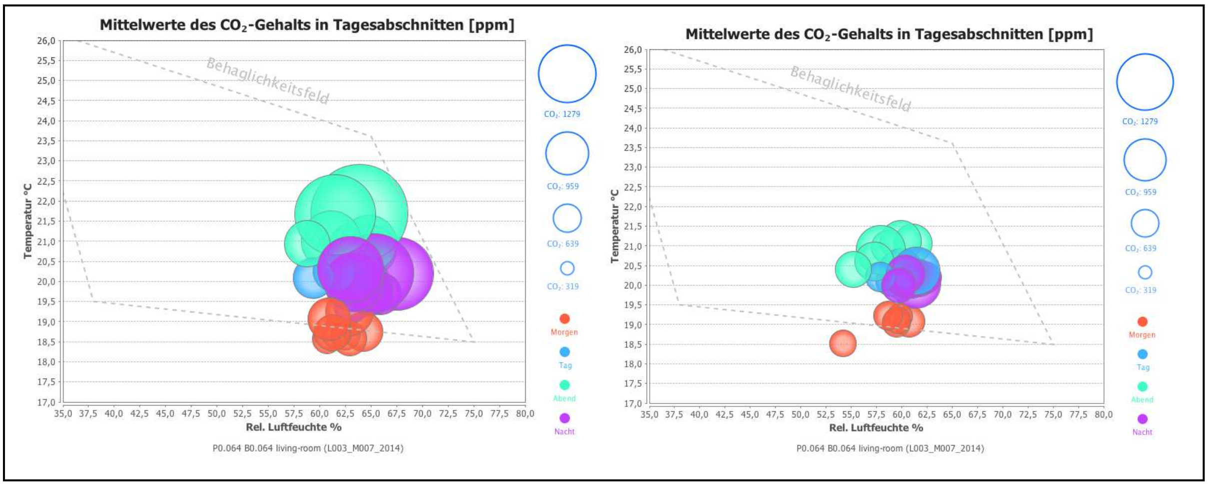

Figure 9: “Bubble” diagram for week 1 (without assistance) and week 2 (using LUQA monitor) in the living room of the participant P0.164

The CO_2 concentration has not only major significance for the evaluation of indoor air quality but also the relative humidity. As prevention for moisture on the walls, the relative humidity combined with indoor air temperature should not be higher than a certain amount, so the dew point of the indoor air will not be undercut.

In Figure 10 below, it is shown that in the household P0.064 relative humidity has fallen in the second week in two rooms.

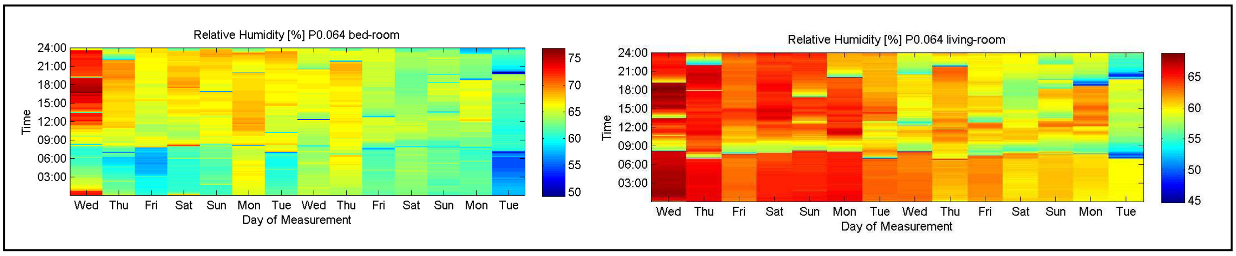

Figure 10: Heat map of relative humidity and absolute humidity over two weeks (first week without a LUQA monitor and the second week with LUQA monitor) in bedroom (left heat map) and living room (right heat map), P0.064

It was only possible to reduce the relative humidity, through raising the indoor air temperature or by constantly airing. Participant P0.064 did both (temperature and relative humidity profiles to see in the Figure 11), which is the reason for higher energy consumption in the second week.

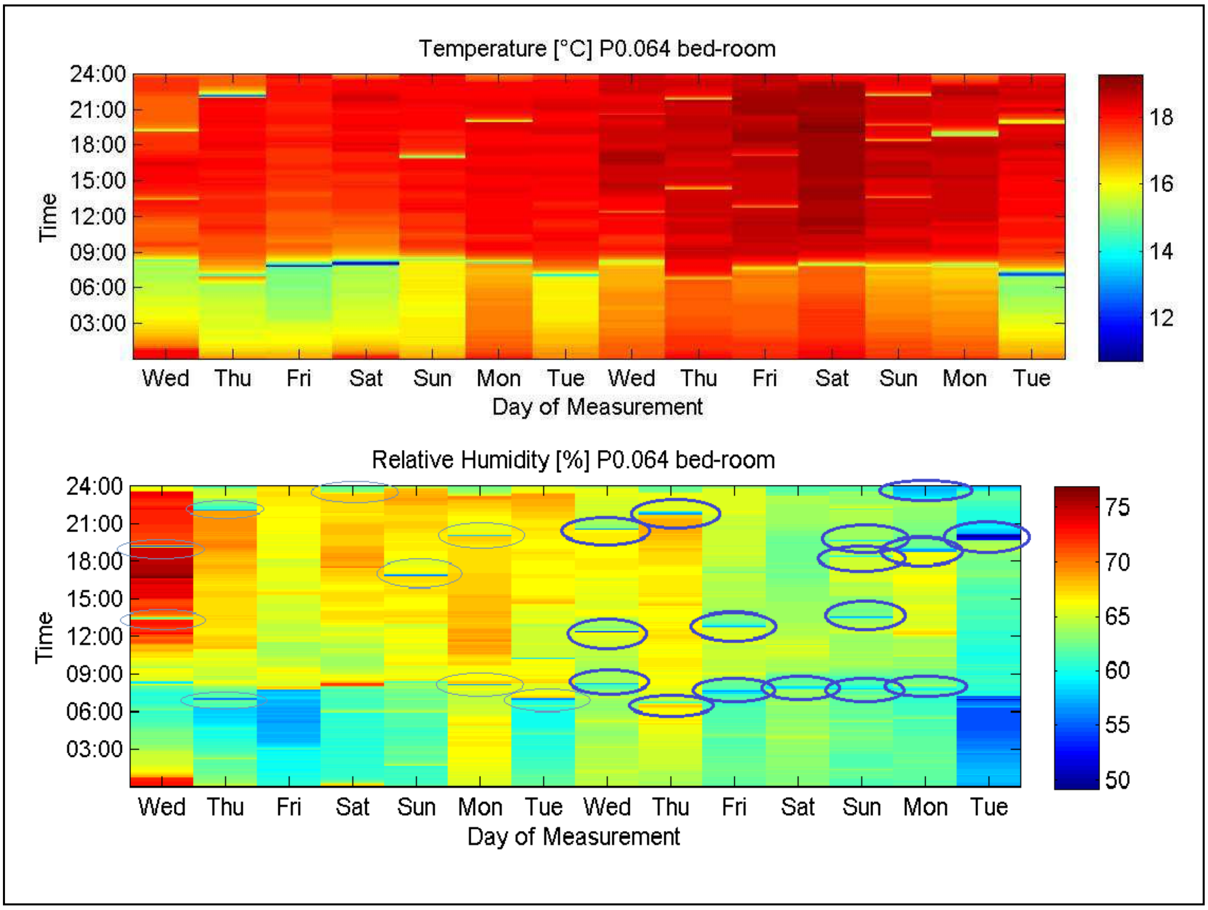

Figure 11: Heat map of indoor air temperature and relative humidity over two weeks (first week without and the second week with LUQA monitor) in bed-room, P0.064

Measurements combined with home automation + LUQA IAQ monitor

Next we will discuss some measurements from households using a home automation system for single room temperature control and IAQ Luqa monitor in the same time.

Figure 11 shows the change of indoor air quality between two weeks of measurement represented with mean CO2 concentration.

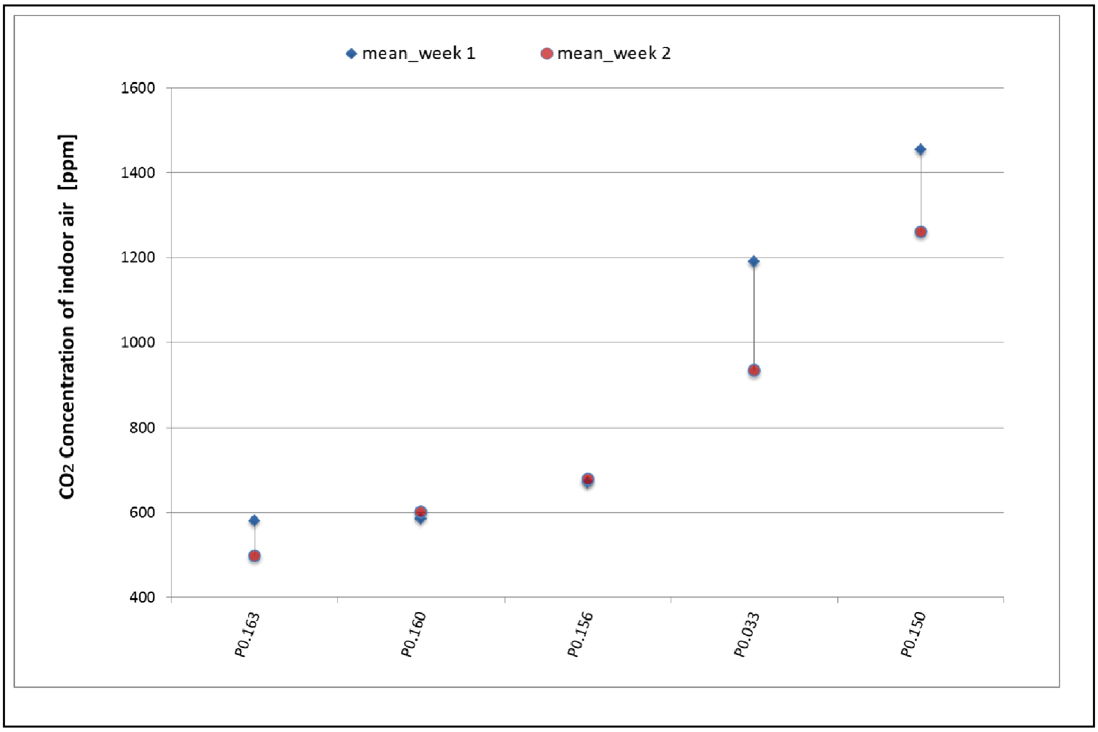

Figure 11: Mean CO2 concentration in week 1 (without assistance devices) and week 2 (using LUQA monitor and smart home system) in the living rooms of the households

As seen in Figure 11, three of five households which used both assistance devices reached improvement of the indoor air quality.

The shifting of the CO_2 concentration density from a higher level in week 1 to lower level in week 2 in the bedroom and the living room is visible in Figure 12. As the participant P0.033 had both systems in the second week it was unclear which (actions) behaviour mostly influenced the result.

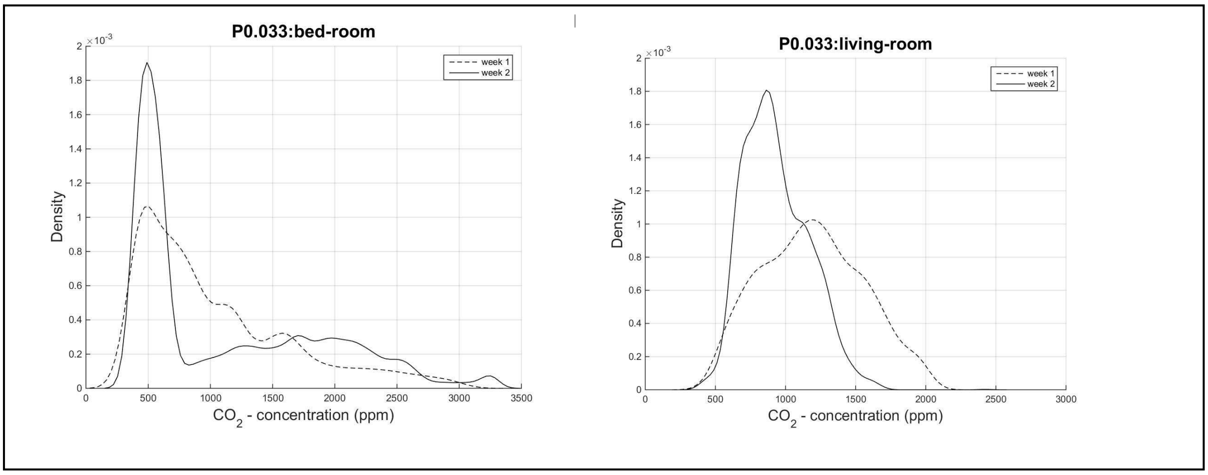

Figure 12: Density of CO_2 concentration in the week 1 (baseline) and week 2 (using LUQA monitor) in the bedroom and the living room of the participant P0.033

According to the LED lights of the LUQA IAQ Monitor a green and red line were drawn in the CO_2 density graph to simulate the limits which are included in the LUQA monitor (Figure 13).

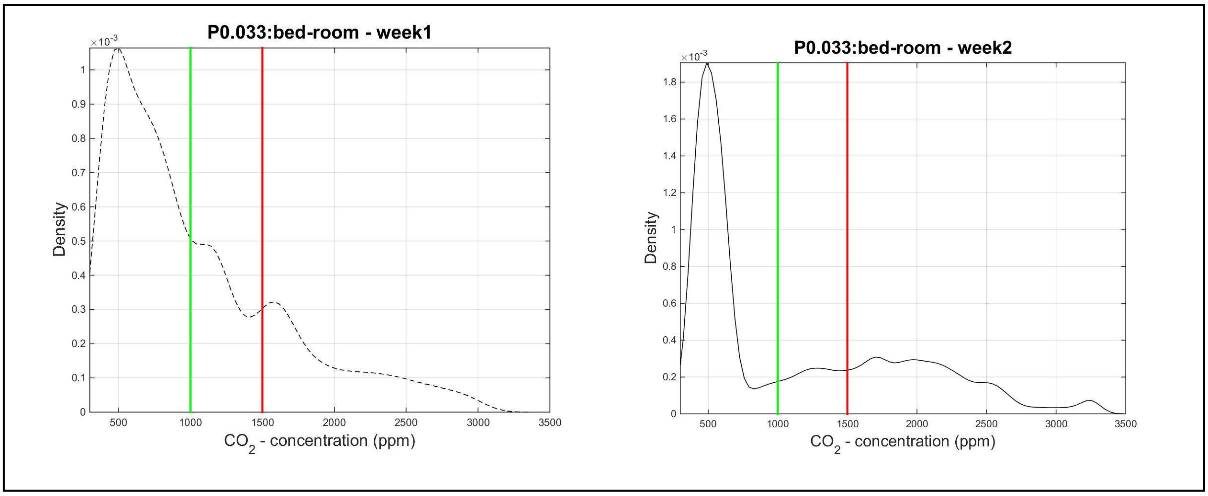

Figure 13: Density of CO2 concentration in the week 1 (without LUQA monitor), bed room

The influence or the use of the smart home system on example household P0.033 is shown in Figure 15. The distinct reduction of indoor air temperature during the night and also during the day (absence time) is evident in the temperature heat map. Overheating periods are also not very distinctive as in week 1.

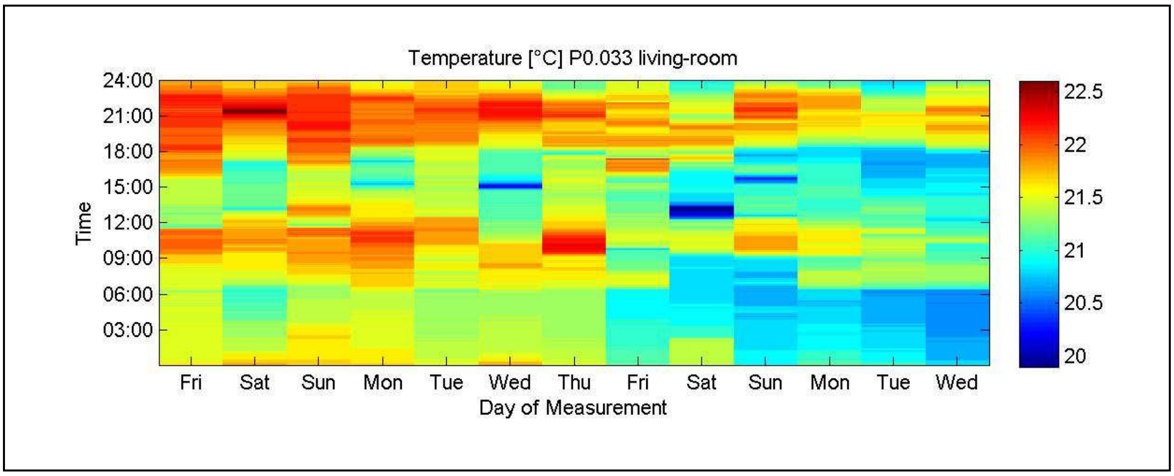

Figure 15: Heat map of indoor air temperature over two weeks (first week without any system and the second week with LUQA monitor and home automation system) in living room, P0.033

Figure 16 below illustrates clearly the temperature profile at different time periods during the day for week one (yellow) and week two (blue) Participant P0.033 had, in the second week, in all day time periods, a lower indoor air temperature and the spreading of the temperature was much higher in the second week. That shows that the temperature settings did work and that the indoor air temperature was not constantly on the same level. Also the mean temperature level sank over the whole day.

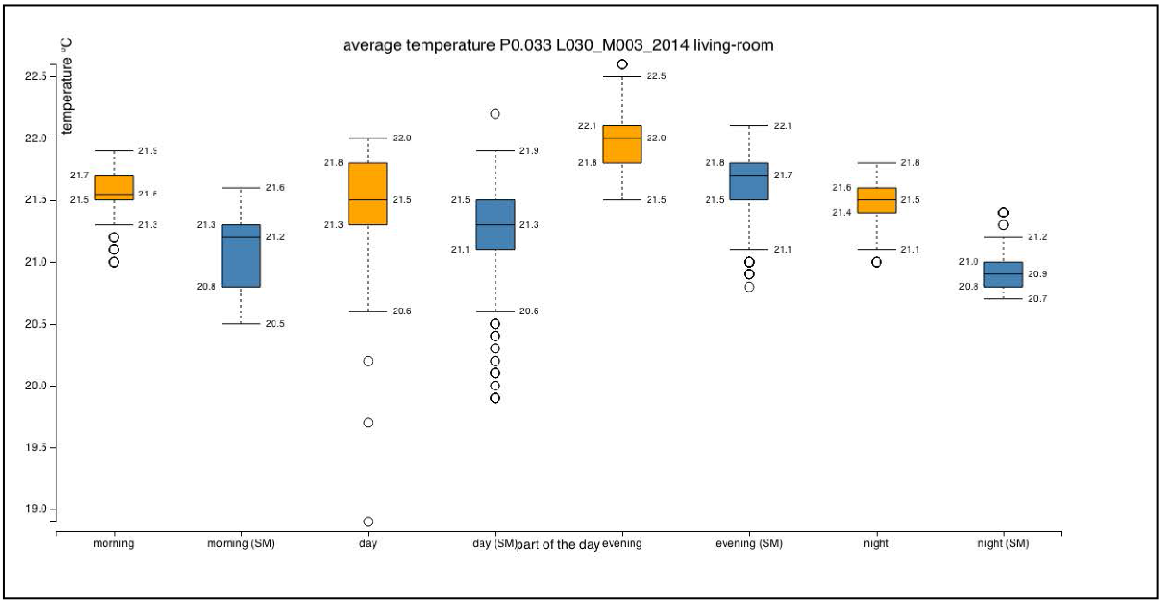

Figure 16: Box plot of the mean temperature on four daytime periods in living room, P0.033

Measurements with a home automation system

Using a smart home system, the participants had an opportunity to set the different indoor air temperature for each room separately according to the appointed temperature (Figure 17). Some of the participants did this without knowing the real temperature in the room beforehand. These participants had much higher energy consumption in the second week without actually noticing that the temperature in the second week was higher.

Figure 17: Appointed temperature profile on RWE Smart Home GUI, for weekend in living room, P0.033

Many participants decided to set the room temperature to a higher level than before and to keep it high much longer than they normally did before. In some cases the participants did not even adjusted a temperature profile and used the system manually as they did before. t This explains why in many cases additional energy consumption (Figure 18) resulted in week 2.

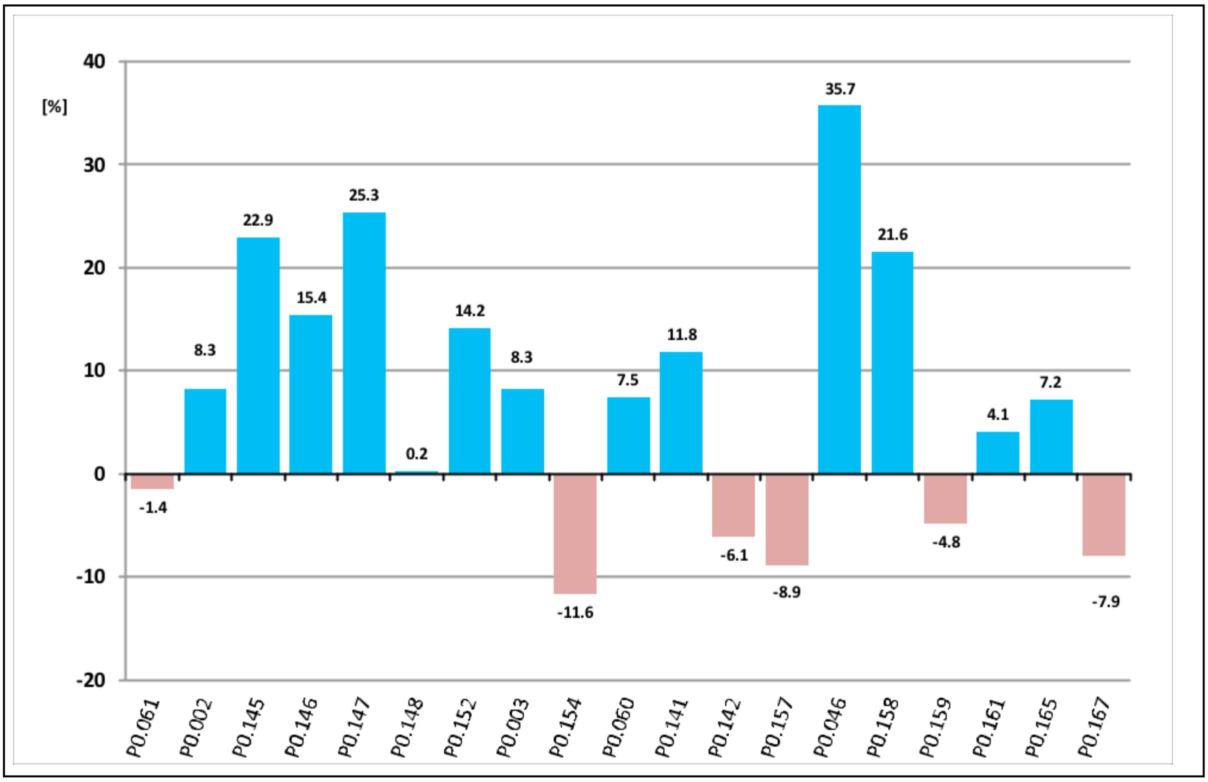

Figure 18: Calculated heat energy savings and additional consumption in the second week using smart home system

The heat map in Figure 19 shows the difference between the two weeks in the temperature distribution of household P0.145 which achieved energy savings during week 2. The lower temperature level during the night and over the day is recognizable. Also the CO_2 concentration in the second week sank reasonably.

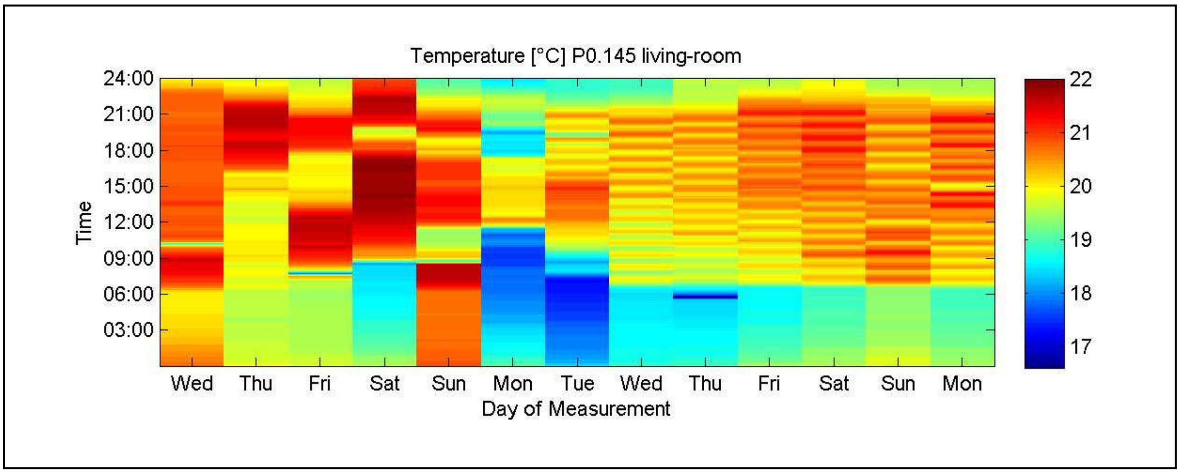

Figure 19: Heat map of indoor air temperature over two weeks (first week without any system and the second week with home automation system) in the living room, P0145

It also shows a steady temperature profile in the second week (from Tuesday to Monday) using a smart home system and very irregular profile of overheating without a smart home system. In behaving this way or rather using these temperature settings with home automation system participant P0.145 achieved an energy saving of about 22.9%.

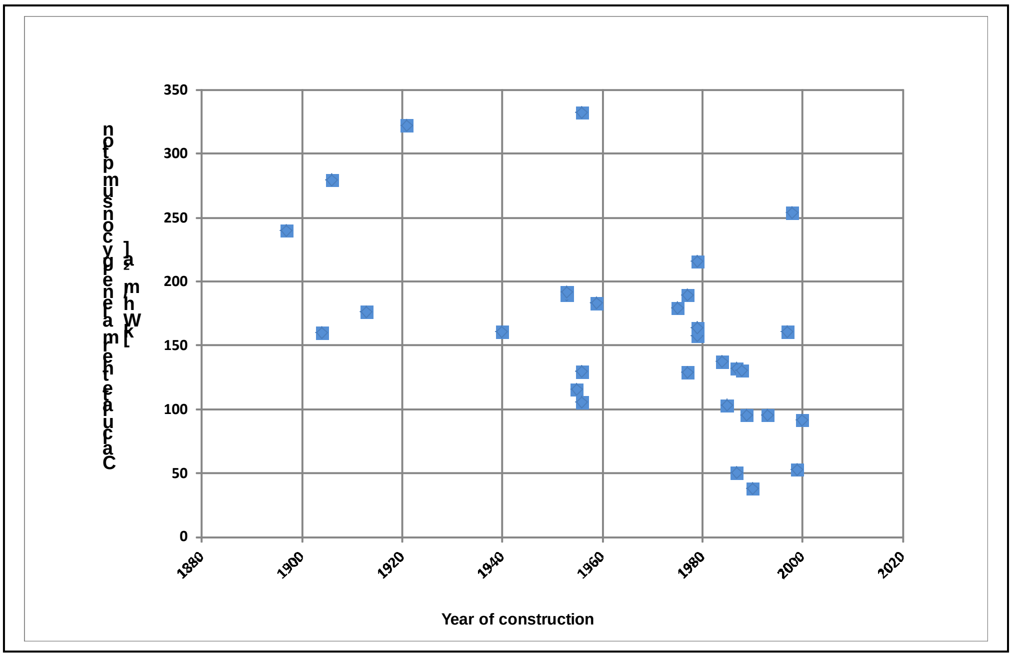

Figure 21: Calculated thermal energy consumption in the week 1 in all households regarding to year of construction

If we look at 21, there is a certain decrease of heat energy demand in the area of the new houses. However there are also some households with new buildings and large heat energy consumption. This illustrates that user behaviour has numerous influences on heat energy consumption and it is not simply down to the fabric of a building.

Conclusion

To record user behavior regarding energy consumption - further measurements were repeated in a new field test over two weeks last winter in 40 households. The first week was used to discover the baseline concerning indoor air quality and heat energy consumption. In the second week two systems were deployed a LUQA IAQ monitor and smart home system. Using a LUQA IAQ Monitor the indoor air quality of 50% of households rose significantly.

Heat energy savings resulted from using both systems. A hundred percent was not achievable nevertheless about 77% of the households has achieved energy savings using a LUQA monitor of between 1.4% and 31% even if the LUQA monitor was designed only for assisting in indoor air quality. About 67% of the households which used the smart home system achieved energy savings of between 5% and 25%.

Via feedback to the user, the indoor air quality improved in those households that previously had a poorer air quality using the CO_2 and relative humidity sensors for an indication of indoor air quality it is possible to increase the energy efficiency in the field of airing due to more purposeful user airing behavior. Those users recognized through the indoor air quality assistance device that airing was needed and in doing so could prevent moisture damage to the building. Households with very high indoor air quality and relatively high heat energy consumption now were able to allow less airing periods and so achieved more energy efficiency.

In many cases mistakes were made in installing or in the settings of the systems. Therefore it is recommendable to check if the used system really does what it should do and if the settings are correct. In many cases participants could install the devices themselves, but in 60% of the cases they needed help. It cannot be concluded based only on a field test if the use of such devices as the LUQA IAQ monitor is of permanent benefit. The feedback from the participants regarding the use of the devices was in any case very positive and many participants aim to purchase such devices in the future. The saving potential we identified is significant enough to justify further research.

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Understanding domestic appliance use through their linkages to common activities

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Abstract

Activities are a descriptive term for the common ways households spend their time. Examples include Daily routines such as cooking, doing laundry, and Computing. Smart energy meter data can be used to generate time profiles of activities that are meaningful to households' own lived experience. Activities are therefore a lens through which energy feedback to households can be made salient and understandable. This paper demonstrates how hourly time profiles of household activities can be inferred from smart energy meter data, supplemented by appliance monitors and environmental sensors. In-depth interviews and home surveys are used to identify appliances and devices used for a range of activities. These relationships between technologies and activities are captured in an 'activity ontology' that can be applied to smart meter data to make inferences on hourly time profiles of up to nine everyday activities. Results are presented from six homes participating in a UK trial of smart home technologies. The duration of activities and when they are carried out is examined within households. The time profile of domestic activities has routine characteristics but these tend to vary widely between households with different socio-demographic characteristics. Analysing the energy consumption associated with different activities leads to a useful means of providing activity-itemised energy feedback, and also reveals certain households to be high energy-using across a range of activities.

1 Introduction

Using remote monitoring to identify when, for how long, and how often different activities take place in the home as part of everyday life is of increasing interest, now smart meters, sensors and monitors are becoming more widely available. These activity recognition efforts have mainly been focused on healthcare applications, including assisted living and tele-rehabilitation. Designing and deploying sensing technology to reliably identify key activities associated with health monitoring usually involves multiple sensors ranging from switch/pressure sensors to occupancy sensors, sensors for measuring walking patterns, physiological condition, different wearable sensors, and environmental sensors.

With the emergence of smart homes and home energy management systems (HEMS), autonomous activity recognition is recognised as an important enabler of home automation more generally. In this paper, we propose an approach for domestic activity identification based on smart energy meter data only. With large-scale roll-outs of smart meters that have already occurred or are about to occur in many countries worldwide, domestic activity identification based on smart meter data becomes very attractive as it does not require any additional sensors and relies on using already available data collected for energy monitoring and billing purposes. As well as enabling advanced HEMS, activity recognition using smart meter can also be used to provide meaningful and timely energy feedback, since it yields insight into households' activities and their consequences for energy consumption.

This paper develops an activity-centric approach to understanding energy use in terms of the time profiles of activities, both routine and non-routine, that constitute the majority of life at home. This approach can be applied to provide novel and effective forms of energy feedback. The overall aim is to improve the value of HEMS by disaggregating the total energy consumption measured by the smart meter and linking these disaggregated data to domestic activities. This builds on previous work in which we propose an algorithm for domestic activity identification using smart meter data and demonstrate its potential using one test house [1]. In [2], we extend this approach by integrating qualitative data from household interviews and physical home surveys into the activity recognition process, and illustrate this multi-step methodology on two case study homes. In this paper, we focus on scaling up the activity recognition methodology and providing a detailed analysis of empirical findings with respect to temporal variation of activities and their energy usage patterns. We use data from six households with different socio-demographics, and analyse the temporal consistency or variability of activities within a household, as well as the extent of activity time synchronisation across households.

The paper is organized as follows: Section 2 provides a background to activity recognition using smart energy meter data. Section 3 describes the methodology developed in [1, 2]. Section 4 describes the results using data from six homes participating in a field trial of smart home technologies in Loughborough, UK. Results are presented in terms of activity time-use profiles both within household and between households. Section 5 discusses the key findings and concludes the paper.

2 Background

Domestic activities are what people do at home. Common activities or 'doings' include washing, cooking, laundry, cleaning, watching TV, playing computer games, resting, and so on. Activities may be routine or irregular, may vary or stay consistent between week and weekend, and may involve one or all household members [3].

Activities are meaningful, since households think about their own daily lives at home in terms of activities; they are salient or easy-to-recall; they are appropriate in providing a comprehensive account of life at home; and they are useful as they are associated with decisions and actions that can be influenced by interventions or policy measures.

As people readily understand their domestic life in terms of activities, analysing and interpreting energy usage data is an effective means of providing energy feedback to households [2]. Energy consumption can be broken down and linked to domestic activities to enable activity-itemised energy feedback. This is a more meaningful and informative approach to feedback than conventional energy or cost-based methods.

A key technological challenge to successful activity-itemised energy feedback is reliably identifying a wide range of activities from metering data. While identification of domestic activities using remote sensing has been an active research area for some time, activity identification based on smart meter data has emerged only recently.

Related research has quantified energy services consumed in homes [4,5] or the energy consumption of specific appliances and devices [6]. Such approaches often supplement aggregated smart meter data with plug monitors for specific appliances and environmental and motion sensors to detect occupancy or specific activities such as cooking, washing, or heating [7]. Data gathering can be both sensor-intensive and intrusive, as in cooker-mounted webcams [7].

Our approach uses smart meters that measure the aggregate load and plug monitors that measure individual appliance loads. This is supplemented by non-intrusive appliance load monitoring (NALM) [8, 9, 10, 11], which disaggregates the aggregate load down to specific appliances, using purely data analytical software-based methods. While most NALM approaches rely on high-sampling rate smart meter data, our NALM approach [12] uses low-sampling rate active power data only, sampled at no more than 6sec intervals, akin to smart meter deployments across the UK and Europe.

This is in line with assisted living applications using NALM and smart energy meter data to support patients with Alzheimer’s disease living in smart homes [10]. This application uses high sampling rates (~60Hz) and active and reactive power to identify usage of particular appliances, but appliance usage is not related to specific activities. Also in the assisted living domain, [13] propose an approach for detecting activities using NALM, smart energy meter data, and individual plug monitors, identifying activities such as shopping, media, food preparation, telephoning, and hygiene.

In contrast with these assisted living applications, our approach relies on very low sampling rates, mimicking smart meters that will be or have already been deployed at national scales. Our approach also focuses on identifying activities linked to energy consumption as a basis for effective energy feedback.

3 Methodology

We develop an activity recognition algorithm by identifying appliance usage events via NALM [12] and by defining activity ontologies using qualitative data from interviews and physical home surveys. In this section, we briefly describe the resulting multi-step methodology, and discuss the challenges associated with activity recognition from readily available data, and how our methodology addresses these challenges. An extended explanation of the methodology is presented in the previous work [2] and is summarised here:

1. Define a set of energy-oriented activities to characterise everyday life at home.
2. Collect real-time energy and environmental data using energy monitors and environmental sensors. Collect data on home and household characteristics including appliance ownership and use patterns.
3. Disaggregate energy data (NALM) [12].
4. Map relationships between activities and technologies to build an 'activities ontology'.
5. Make activity inferences from disaggregated real-time data using activities ontology [1].
6. Validate inferences using time diaries and household visits.

3.1 Activity selection

The set of activities that is usually studied in energy-related research is narrowly focused on high consuming activities such as cooking or lighting [4]. In line with the UK's Office of National Statistics (ONS) time-use study [14], and discussed in [2], we identify 16 activities that are comprehensive, parsimonious, and energy oriented and group them into 4 categories: Daily Routines, Interacting, Computing and Leisure, and Other Activities. Daily Routines category comprises 6 activities: cooking, eating, washing, laundering, cleaning and sleeping. Interacting consists of communicating (with people outside the home) and socialising (with people at home). Computer and Leisure consists of 4 activities: watching TV, listening to radio or music, playing computer games, and all other computing. Other Activities consists of the 4 remaining activities including hobbies, working and caring.

3.2 Data collection

In each monitored house, a mix of quantitative and qualitative data is collected. Quantitative data comprises aggregate active power in Watts (W) sampled every 6-8 seconds, and (optionally) environmental data such as temperature, humidity and occupancy to detect activities that do not primarily use electricity, such as washing using gas-based water heating, or cooking on a gas hob. In addition to aggregate power, we also measure up to nine appliances using plug monitors.

Collected qualitative data comprise: (1) physical home surveys; (2) semi-structured household interviews on activities and video ethnography on technology ownership and usage. The interview and video data are coded (analysed and interpreted) in terms of domestic routines and are used primarily for mapping relationships between activities and technologies into an 'activities ontology' for each household. Home surveys provide the spatial layout of rooms and devices, and help towards building the ontology. The appliance time diaries and electricity data are used for the disaggregation and activity inference algorithms, described further below. Details of our data collection platform can be found in [15].

3.3 Energy disaggregation

The task of Non-intrusive Appliance Load Monitoring (NALM) is to disaggregate a household's total energy readings down to specific appliances used. NALM effectively creates virtual power sensors at each appliance using purely software tools. Many NALM methods have been proposed in the literature, that mainly consist of edge detection and feature extraction, followed by classification. NALM research, especially on active power loads at low sampling rates (lower frequency than 1Hz), is still challenging with 70% or less accuracy in real household environments with many appliances. A review of approaches is given in [9]. In this paper, we use the approach proposed in [12] based on decision tree (DT), which has the advantages of minimal training and high performance at low sampling rates of active power data only. The Decision Tree (DT)-based method of [12] consists of training and testing phases. During training, for each known appliance maximum upraising and decreasing edge is recorded and used to design a decision tree. Labelling of signatures detected by the NALM algorithm is dependent on data from individual plugs or/and self-completed appliance time diaries. The output of testing is a list of appliances used together with the start and end time of their operation. Output is validated in a subsample of homes against self-completed time diaries by householders recording the frequency and duration of appliance usage (appliance time diaries).

3.4 Activities ontology

The output of NALM, i.e., the list of specific appliances used with their timestamps, together with data from individual appliance monitors (IAMs) can be mapped to particular activities through the use of 'activity ontologies'. An activity ontology maps out all known relationships between activities and the energy-using technologies (devices, appliances) used in those activities. The ontology also captures relationships between activities or technologies and other environmental information such as occupancy of particular rooms, temperature/humidity change, etc. The purpose of the ontology is to link measurable real-time information to the set of activities characterising everyday life at home.

A particular energy-using technology can *definitely, possibly,* or *indirectly* indicate that an activity is occurring. These are distinguished in the ontology through codes for *marker technology, auxiliary technology,* and *associated activity,* respectively. Whereas marker and auxiliary technologies allow activity inferences with different degrees of certainty, the 'associated activity' relationships allow inferences about activities that are otherwise not indicated by technology use. An associated activity refers to the use of technology that is a marker for another activity, which is concurrent or linked with a second activity (e.g., switching off bed lamp at night might indicate going to sleep, hence it is an associated technology for the 'sleeping' activity).

An example of part of an ontology is shown in Figure 1 in matrix form (ontologies can also be represented diagrammatically). The rows in the ontology refer to technologies and the columns to activities. Activities are grouped into the four categories of Daily Routines, Interacting, Computing and Leisure, and Other Activities. Activities are traffic-light colour coded such that green indicates an activity can definitely be inferred, red indicates that an activity is not inferable from the current data, and amber refers to an activity that can possibly be inferred if readings are available from IAMs since the technology cannot be reliably inferred by the NALM algorithm.

The mapping of relationships between technologies and activities (each cell of the matrix in Figure 1) show marker technology as an 'x', auxiliary technology as a '~' and associated activity as a 'o'. Each technology contains a descriptor of its location and a small narrative regarding when and how often the technology is used based on the qualitative data. Narrative data shown in green font is from the video ethnography; narrative data shown in red font is from the validation visit (see Step 6 on pp.3).

	ACTIVITIES																TECHNOLOGY-ACTIVITY RELATIONSHSIPS - additional info			
	Daily Routines						interacting		Computing and Leisure				Other Activities							
TECHNOLOGIES	cooking	eating	washing	laundering	cleaning	sleeping	communicating	socialising	tv	radio	games	computing	hobbies	caring	working	other	Location / Room	Fixed / Mobile	When Used	Frequence of Use
breadmaker	x																kitchen	(fixed)	after dinner	3 times / week
toaster	x	o															kitchen	(fixed)	breakfast	
omelette maker	x																kitchen	(fixed)		
fridge	x																kitchen	fixed		
crockpot	x																kitchen	(fixed)		
microwave	x	o															kitchen	fixed	breakfast - porridge (the only thing microwave is use	
kettle	x	o						o									kitchen	(fixed)		
food mixer	x																kitchen	(fixed)		
electric oven & hob with extractor fa	x																kitchen	fixed		
dishwasher	x																kitchen	fixed	2-3am	Every night from 2am-ish
washing machine				x													kitchen	fixed	Overnight	Several times a week
tumble dryer				x													kitchen	fixed		
DAB radio	~	~		~ [ ]						x							kitchen	(fixed)		on in background all day (t=
gas fire																	lounge	fixed		
stereo, speakers										x							lounge	(fixed)	every day (t=4.00)	during cup of tea in afterno
VHS VCR								~	x								lounge	(fixed)		
PVR (= hard drive?)								~	x								lounge	(fixed)		
TV								~	x				o	NA [~]			lounge	(fixed)		
record player								~		x							lounge	(fixed)	once a week (t=4.00)	
TV								~	x								dining room	(fixed)		if there's a clash of schedul
DVD player								~	x								dining room	(fixed)		
catch-up TV								~	x								dining room	(fixed)	not used very much (t=1.50)	

Figure 1: Example of part of an activity ontology.

3.5 Activity inferences

The NALM algorithm introduces some uncertainty, due to possible mis-classification if a power signature of one appliance is classified as another due to similarity of active power signatures. Another source of uncertainty comes from the stochastic nature of human behaviour, which is common to other domestic activity recognition studies. These uncertainties are called disaggregation uncertainty and context uncertainty, respectively [1].

To make reliable inferences given these uncertainties, we use Dempster-Shafer (DS) Theory of evidence (see [1]). DS is a proven to be effective in case of high uncertainty and multiple sources of information; it can make the distinction between uncertain and unknown information and combine evidence from different sources to reach a consensus with some degree of belief.

Disaggregation uncertainty, estimated during NALM training, and context uncertainty, obtained heuristically using the activity sample data, are integrated into the model as in [1]. Further details on the activity inference algorithms are provided in [1].

3.6 Inference validation

The final step of the methodology validates inferred activity data in semi-structured interviews with households in which inferences are compared against self-completed time diaries for the same period [2]. Discrepancies are identified and attributed, most commonly to missing time diary entries or to inference inaccuracies linked to mis-specifications in the activity ontologies. These are then corrected as shown by the red cell entries in Figure 1. In some cases, the final validation step identifies activities that do not occur in a particular household. These can then be removed from the ontology (see light red columns in Figure 1).

3.7 Practical challenges and solutions

Not all domestic activities are inferable using the proposed methodology with available energy data. Activities cannot be detected if they are not tied to an energy-consuming technology, if they do not have a marker technology, or if they are only associated with technologies that cannot be reliably detected due to, for example, low power operation. The set of activities that cannot be detected reliably varies from household to household, but generally always includes sleeping, eating, socialising and caring.

Our approach faces a number of challenges similar to those in the existing body of research on energy disaggregation and appliance usage. Table 1 lists how we address each of these challenges.

Table 1: Challenges in activity recognition and our approach.

Challenges	**Our approach**
<u>Knowability:</u> Activities cannot be inferred if they lack any direct or indirect association with energy-using devices or with specific and measurable environmental conditions (e.g., motion in particular rooms).	*Time diaries cover full set of activities (but only for specific days). Ontology distinguishes associated technologies which mark an activity taking place at the same time as another activity.*
<u>Reliability</u>: Disaggregation routines cannot consistently capture the use of devices that are highly mobile or that operate on battery power (either permanently or while not plugged in). Conventional distinctions between audio, visual, communication, and computing devices are rapidly collapsing. This increases the difficulty of making inferences about specific types of ICT-related activities.	*Mobile or battery-powered devices are not used as marker technologies in ontology. ICT-based activities can be collapsed into a higher order 'all ICT-related' activity to reduce risk of missing inferences.*
<u>Ambiguity</u>: Devices used for several different activities cannot be used unambiguously in making activity inferences.	*Ontology distinguishes marker from auxiliary technologies. Marker technologies identify when an activity is definitely going on. Auxiliary technologies identify when an activity may be going on.*
<u>Validity</u>: Inferences made about energy services or appliance use from disaggregation routines	*Self-completion time diaries and structured time-diary based interviews are used to validate activity*

have unknown reliability (accuracy) or validity in terms of households' lived experience (appropriateness).	*inferences.*
<u>Coverage</u>: Heating and lighting are both energy-intensive services but not activities *per se*. Heating and lighting-related energy use could be apportioned to activities taking place in specific rooms for time periods during which those rooms are lit or heated, or could be accounted for separately.	*Heating- and lighting-related energy is included in separate energy service categories when inferences are expressed in energy terms (rather than as time-use profiles).*
<u>Accuracy</u>: Extracting individual appliance usage from data with Smart Metering Equipment Technical Specification (SMETS) specifications [14], i.e., active aggregate power only at very low sampling rate of the order of 10 seconds is tricky because some appliance signatures are the same, or some signatures are too low-power and 'hidden' by other appliances concurrently operating.	*Data checking & cleaning, building library of known appliance signatures, using appliance survey, developing new non-intrusive appliance load monitoring algorithms that can detect with accuracy >80% individual appliance loads from one-dimensional and low resolution data, and appliances overlapping in time use.*
<u>Accountability</u>: The accuracy of the disaggregated energy use as virtual sensors must be used as evidence towards making a decision towards inferring an activity.	*Using a probabilistic approach towards combining evidence from multiple heterogeneous sensors to infer activities, incorporate and discount uncertainty from incorrectly identified appliance events, reliable ontology.*

4 Results

In this section, we apply our approach to make inferences about activities taking place in six households over a period of one month (October 2014). We have chosen this month since it is not typically associated with holidays, periods or absence from homes, or other obvious disruptions to routine domestic life. Our main aim is to demonstrate the potential of our approach by examining the time profiles of household activities in terms of their timing, duration, and consistency day to day and week to week within a given household, as well as between different households. These time-use profiles are a necessary step to understanding and representing energy use in ways that are meaningful to households as a basis for feedback.

The monitored houses are of different occupancy and age groups (e.g., retirees, working couples, families with children). These households were chosen with a mix of technical and non-technical backgrounds, and were fitted with energy monitoring equipment (total gas, total electricity, and electricity for up to 9 individual appliances (IAMs) via submetering), environmental sensors and smart home kit to automate/pre-schedule appliance and heating use.

Table 2 provides a brief description of the six households, and the activities we could infer using the active power data (aggregate and appliance-specific) and home surveys. No time diaries of appliance use were available for all households, which had implications on disaggregation certainty, since we could not verify some appliance signatures.

The sixth column of Table 2 shows the percentage of electrical appliances out of the total number (shown in the third column) of known measurable electrical appliances in each home that could be detected reliably via our NALM algorithm (column 5) or directly metered from a plug monitor (column 4). We can detect at least 48% of appliances in most houses, but as the range of appliances increases, we are limited by our signature database, which contains all signatures we have been able to label via submetered devices, or time diaries from previous validation work. (Time diaries of appliance use were not available for the homes in Table 2.) In all cases, NALM significantly supplemented IAM to detect almost 50% of commonly used appliances in the households, as well as identifying auxiliary technologies (inc. minimum demand or base load) to identify activities such as eating and sleeping.

Table 2: Household characteristics, appliance detection, and activities that can be inferred with different levels of uncertainty.

Household ID	Household Size & Composition	Total number of known measurable electrical appliances	Total number of appliances detected by IAM	Total number of appliances detected by NALM	Appliance Detection (% of known appliances in home)	Inferable Activities (n = total number of inferable activities for each household)
2	Family of four with two young children	17	9	5	82	Cooking, eating, washing, laundering, sleeping, socialising, watching TV, listening to radio (n=8)
4	Couple of pensioners	55	14	18	58	Cooking, eating, laundering, watching TV, sleeping, hobbies, computing (n=7)
5	Family of four with two children in early teens	44	14	7	48	Cooking, eating, laundering, sleeping, watching TV, cleaning, computing, hobbies (n=8)
8	Couple of pensioners	43	11	12	53	Cooking, eating, washing, laundering, cleaning, sleeping, watching TV, computing (n=8)
10	Family of four with two young children	34	9	8	50	Cooking, eating, washing, laundering, sleeping, watching TV, computing (n=7)
19	Family of four with two children in early teens	32	10	10	63	Cooking, eating, laundering, sleeping, socialising, watching TV, listening to radio, ICT-related games (n=8)

While we can detect most high load appliances, those low power appliances (<20W) such as electric toothbrush, printer, router, DAB radio get 'lost' in the aggregate data and account for the percentage of appliances that cannot be detected. Another set of appliances that we cannot detect, and are not included in the above total, are gas-based, battery-based and mobile appliances such as smart phones, tablets, radios and digital cameras.

We build activity ontologies for each of the six households using data from the home survey, household interviews and video ethnography. Table 2 shows all activities that can be identified based on the detected appliances mapped to these activities in the ontology. We can detect in most cases all six activities of daily routines, all activities of ICT-related leisure, and in some cases socialising, hobbies and games. Socialising is partly inferred from the quantitative data gathered from Listening to radio, but could be inferred with higher certainty if we had more qualitative data describing patterns of socialising and/or appliances associated with socialising for the household. We can only detect low load appliances, such as the CD player, associated with the Listening to radio activity in House 2, because it is submetered.

In the following sections, we summarise our main results in response to three questions:

1) *When and for how long do activities occur each day?* We use stacked time duration plots to show average activity time profiles (including durations) during a day over the week and weekend, for each household.

2) *How consistent are the occurrences and durations of activities over time?* We use rose charts to show averaged monthly time durations of activities across hourly time slots.

3) *Can activity time profiles provide meaningful feedback on energy use?* We use data tables to show the total energy consumption per month per activity for all the households.

The first two sets of results show the time profile of activities and their consistency both within and between households. This is important for analysing the potential flexibility to shift or sequence certain activities in order to manage energy demand. The third set of results identifies the main "activity consumers" of energy, and so the potential for providing tailored activity-itemised energy feedback.

4.1 Activity time profiles per household for typical days

Using Houses 4 and 5 as examples, Figures 2 and 3 show the time use over the activities detected for the two households, as a percentage of the total known time use, for an average weekday and an average weekend day during October 2014.

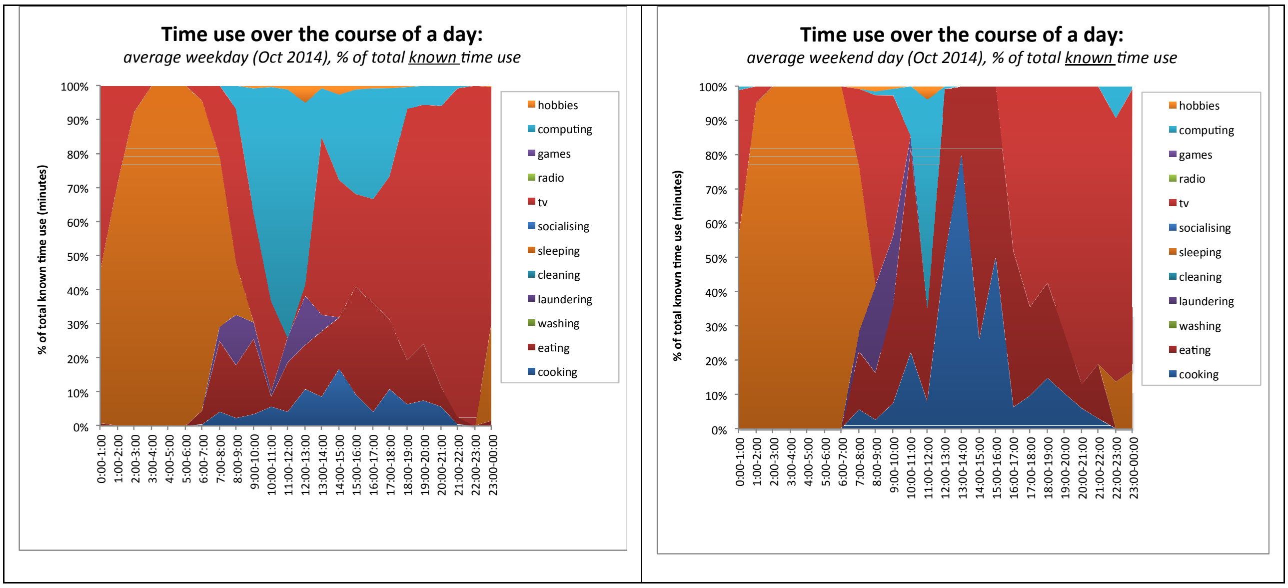


Figure 2: House 4 average weekday and weekend activity time profiles.

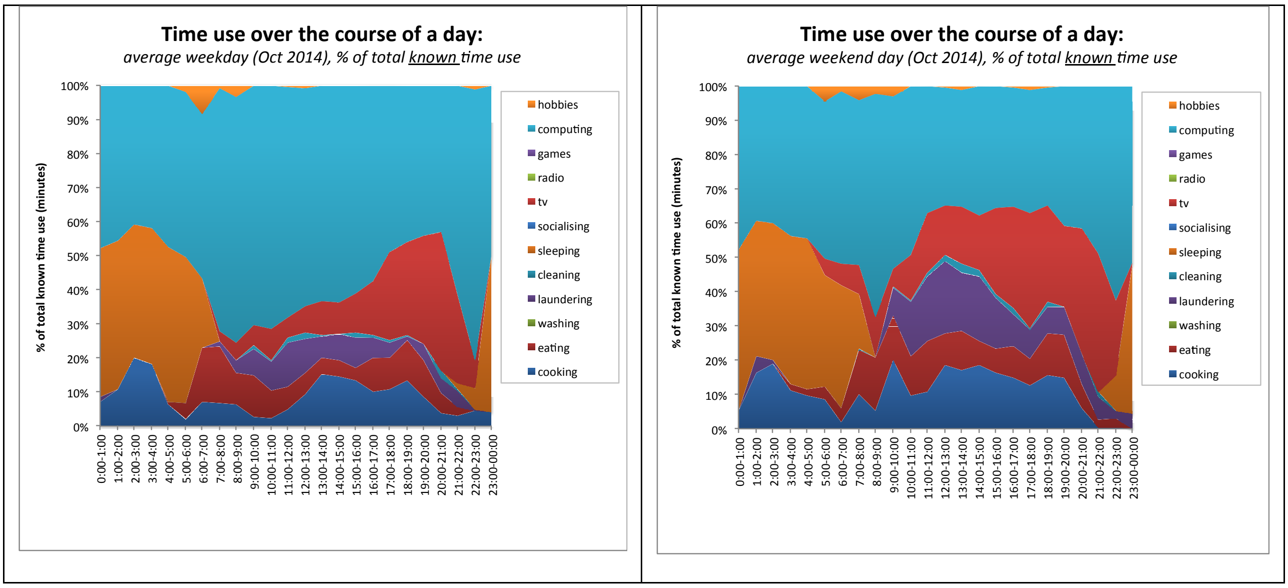


Figure 3: House 5 average weekday and weekend activity time profiles.

House 4 is occupied by a couple of pensioners. The household wakes up every day between 6-7am, and the TV is being left on throughout the day until the late night during weekdays. During weekends, on the other hand, there is markedly less TV watching, less computing, whereas time is allocated more to cooking and eating.

House 5 is a family with two teenage children. Cooking shows marked variation from weekday to weekend, reflecting the changing domestic routines of a household with school age children and working adults not at home during weekdays. Cooking activities at the weekend are more frequent and of longer duration spread throughout the day (Figure 3). We also see that House 5 runs its dishwasher overnight, hence we observe a large time duration of the 'cooking' activity between midnight and 6am. Cooking includes preparing food and drink but also cleaning and washing up afterwards.

A similar variation is seen in the watching TV activity between weekday and weekend, again reflecting a household with children and so a distinctive temporal pattern of meal times, TV watching, and bed time routines which differ markedly on school nights compared to weekends (Figure 3).

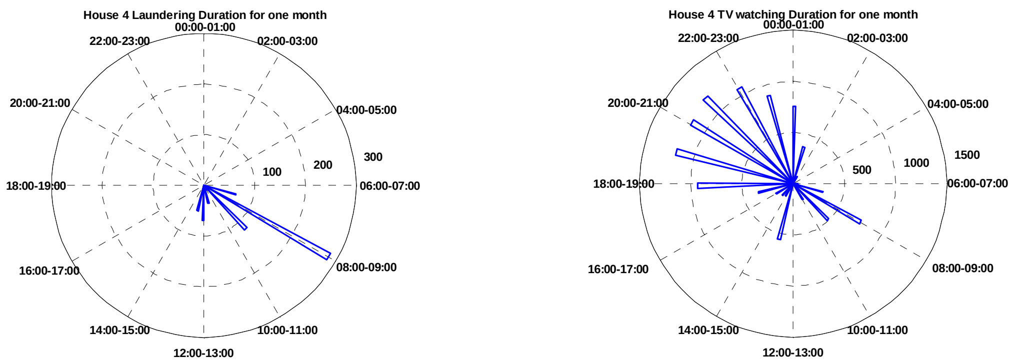
4.2 Typical durations of daily activities, averaged over a month

Figures 4-6 show the distribution of particular activities over a 24 hour daily cycle divided into labelled hourly time slots, beginning at 00:00 and moving clockwise through the morning, afternoon, evening, and night time periods, for Houses 4 and 8, respectively. The radii of the bins in these ‘rose diagrams’ are sized differently according to the activity. All bins show duration in minutes over a month (October 2014).

Both Houses 4 and 8 have the same household composition: two pensioners. The results show key activities which have different roles in households' routines: laundering, computing, TV watching, washing. While washing and laundering are activities in the 'Daily Routine' category of everyday necessities at home, TV watching is a leisure activity, and computing as an activity can be variably linked to work, study, gaming, information search, shopping, communication and so on**.**

House 4 is occupied by two retired adults who are mostly at home during the day, with the TV on throughout the day intermittently. Laundering occurs mostly in the morning as shown in Figure 4. Computing occurs regularly throughout the day, but predominantly in the morning, compared to House 8, also occupied by a couple of retirees, as shown in Figure 6.

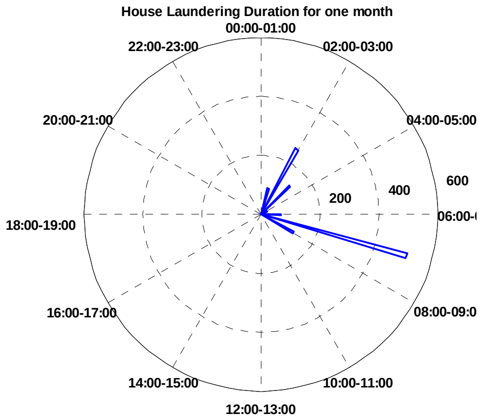
In House 8 there is no laundering activity in the afternoons and evenings (see Figure 5). Instead laundering takes place overnight and in the early hours of the morning as the household is on an Economy 7 tariff and benefits from cheaper overnight tariffs by shifting loads to off-peak hours. House 8 has the same composition as House 4 (two pensioners) and is similarly occupied during the day with the TV on throughout the day intermittently.

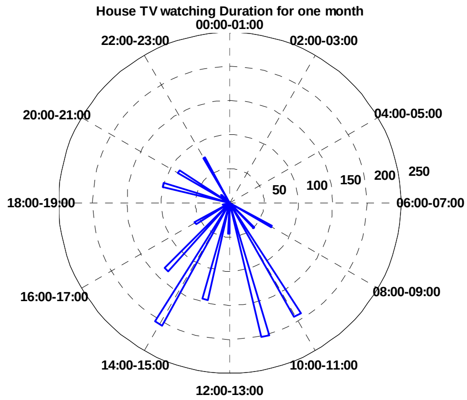


(a) Laundering

(b) TV watching

Figure 4: Total time duration of activities (minutes) in House 4 over a period of one month per hourly time slot: (a) laundering, (b) TV watching.

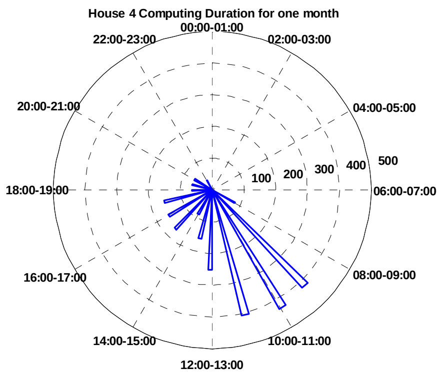


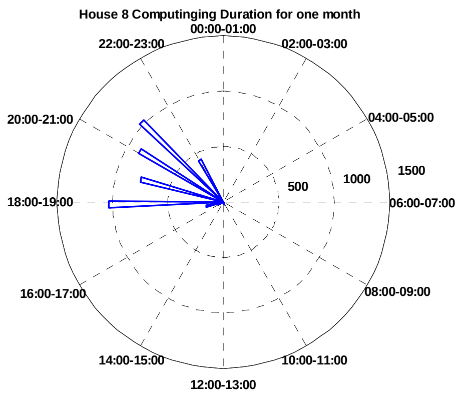


(a) Laundering

(b) TV watching

Figure 5: Total time duration of activities (minutes) in House 8 over a period of one month per hourly time slot: (a) laundering, (b) TV watching.

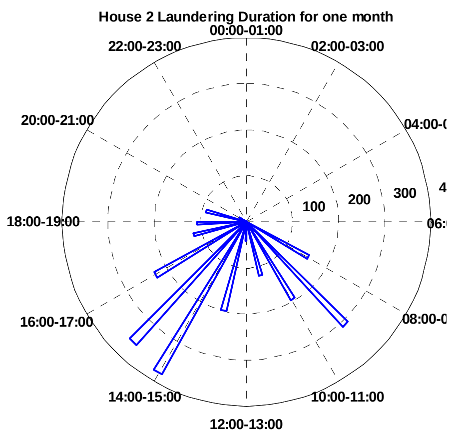


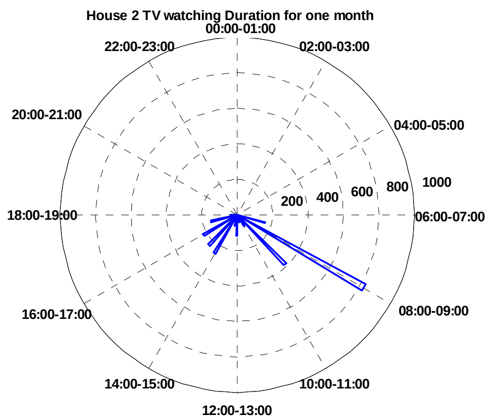


(a) Computing in House 4

(b) Computing in House 8

Figure 6: Total time duration of Computing (minutes) in Houses 4 and 8 over a period of one month per hourly time slot.





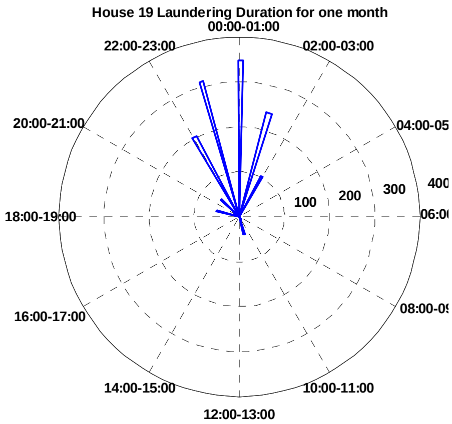
(a) Laundering

(b) TV watching

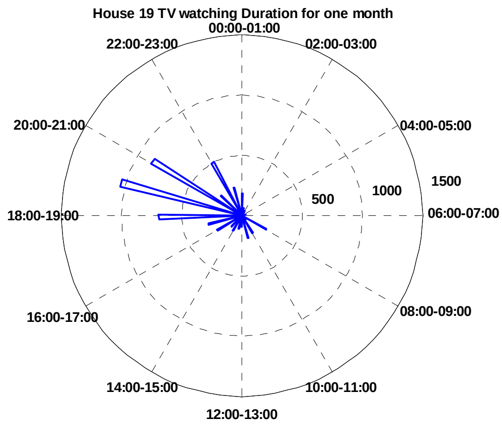
Figure 7: Total time duration of activities (minutes) in House 2 over a period of one month per hourly time slot: (a) laundering, (b) TV watching.

House 2 has a different composition: two adults and two pre-school children. In House 2, the need for laundering created by young children becomes very clear (see Figure 7). Laundering activities are distributed throughout the day for relatively shorter durations than House 4, with the bulk of laundering taking place in the afternoon. The rose diagram also makes clear the importance of the TV watching morning routine in the 8-9am time slot.

House 19, a family with teenage children, like House 2 also does more laundering than Houses 4 and 8 with only retired adults, but the laundering activity takes place late at night (see Figure 8). TV watching is limited to evenings, after a day at school, work and various after-school activities.



(a) laundering



(b) TV watching

Figure 8: Total time duration of activities (minutes) in House 19 over a period of one month per hourly time slot: (a) laundering, (b) TV watching.

Table 3 compares the cooking activity pattern across all 6 houses. Houses 4 and 8 cook a bit less than other houses which matches the households' composition. All houses spend more time on cooking on an average weekend day compared to an average weekday. Both Houses 2 and 10, with young children, spend a higher portion of their time on cooking with respect to other inferred activities compared to Houses 4 and 8, occupied by a couple of retirees.

Table 3: Cooking activity duration in all 6 houses over a month

House	House 2	House 4	House 5	House 8	House10	House 19
cumulative time use (in mins)	286	73	639	162	369	182
% of time spent on cooking over all inferred activities for this household	12.45%	4.25%	10.56%	9.58%	19.76%	8.18%

4.3 Energy consumption per activity

The above results showing time durations of specific activities over typical days or over whole months do not show associated energy consumption. Yet as noted, energy consumption linked to daily activities is an effective basis for providing meaningful energy feedback to households. This may be particularly important for activities over which households have some flexibility as to timings (e.g., shifting loads to off-peak hours) or to durations (reducing loads). The activity inference methodology described above can be used to link part of the electricity consumption of a household to certain activities. This is shown in Table 3 for the six households on which the methodology was tested, where the total energy consumption in kWh over the whole month is disaggregated to the level of activities. Shaded cells represent activities for which we do not have sufficient data to make an inference, e.g., Houses 4, 5, and 19 do not have an electric shower and use hot water from a gas boiler for washing, so the washing activity is not inferable from the available electricity data. Similarly, radio and ICT-related gaming appliances, which have a very low load, can only be obtained via an IAM, present only in Houses 2 and 19.

Table 3: Total electricity consumption per activity (in kWh) for a month.

House / Activity	House 2	House 4	House 5	House 8	House10	House 19
Cooking	75.4 *	33.1	98.3	65.6	67.6 *	37.3 *
Washing	47.7			24.4	1.2	
Laundering	12.9	10.7	79.3	20.3	24.4	4.0
Cleaning			3.8	3.6		
Watching TV	2.8	11.5	17.7	9.7	39.8	19.2
Listening to radio	6.5					0.8
Computing		15.6	68.2	15.6		
ICT-related games						3.4
Hobbies		1.5	11.1			
Total electricity use per house (independent of activity inferences)	337.7	282.3	636.3	422.4	417.0	248.0
% of total electricity use explained by activity inferences (inc. lighting)	44%	26%	44%	33%	32%	26%
Total residual (kWh) per house unexplained by activity inferences	192.4	209.9	357.9	283.2	284.0	183.3
% of residual due to base load	32%	27%	42%	22%	29%	56%
% of residual due to cold appliances	16%	53%	14%	9%	27%	22%

% of total electricity use that cannot be explained by all above (inc. lighting)	30%	15%	25%	46%	30%	16%

* Gas also used for cooking (on a hob).

Of all the activities which are generally inferable from available electricity data, cooking is the main energy-consuming activity. House 5 consumes the most electricity overall, with higher than average demand for computing and laundering. Houses 2, 4 and 19 cook on a gas hob which reduces their electricity consumption for cooking activity.

By relating these values to the time duration of activities, it is possible to benchmark the energy efficiency of appliances in different households. As an example, according to Table 3, House 19 consumes almost 5 times less electricity for laundering than House 8. The activity duration rose plots show that both houses spend about the same amount of time on laundering (see Figures 8 and 5) so it may be that House 19 has a more efficient washing machine than House 8.

Activity recognition cannot account for all the energy use in the home, with a maximum of 44% across the six homes analysed. Homes with electric cookers and showers will have a higher % of total electricity consumption resulting from inferable activities. Electricity that cannot be accounted for using the activity inferences relates to base loads, lighting, cold appliances such as refrigerator, boiler and other battery-operated or low-load appliances that cannot be disaggregated due to the limitations of NALM algorithms operating on very low sampling rate data. Table 3 shows that, after accounting for cold appliances and base load, the unaccounted % of electrical energy consumption drops to less than 46%. House 2, specifically, includes in its 30% unexplained energy consumption, charging of an electric car but we cannot fully disaggregate the entire charging period. Note that these unaccounted numbers include lighting, which in the UK contributes around 16% towards the total consumption [16].

5 Conclusions and Future Work

In this paper, we presented an activity-centric approach to understanding time use and energy use in homes. We tested this approach on six households and provided illustrative results. This approach moves away from a traditional energy-centric approach linked to aggregated energy and cost-related feedback. Activity-centric approaches help users and scientists understand activities in the home in terms of time profiles which are meaningful to households' lived experience.

Our results show that between 4-9 domestic activities can be reliably inferred using electricity data and activity ontologies. These include cooking, laundering, and watching TV. For the six houses on which the method was demonstrated in this paper, 7-8 activities per household could be inferred. Most of the inferable activities have regular weekday time profiles, but weekend activities are less regular. For activities with regular time profiles throughout the week, timings and frequencies tends to change between weekday and weekend. Differences are particularly marked in households with children with associated scheduling of school runs, meal times, TV watching periods, bed times and so on. The timing and duration of activities also varies widely across households.

These results are work ongoing and we plan to do more extensive analysis, both within household and between household, to determine the reliability and implications of our activity-centric approach, and to test its effectiveness as a basis of providing activity-itemised energy feedback to households. We will also develop simplified methodologies for evaluating the quality and accuracy of the activity-inferences.

We plan to develop a self-completion instrument that is less resource intensive and intrusive than the householder interviews which we use to develop the activity ontologies. This will enable our method to be scaled-up alongside a nationwide smart meter roll-out. Specifically: (i) initial household interviews and video ethnography could be substituted by activity-based questionnaires that can be administered by remote or as part of a smart meter installation; (ii) home surveys which could be self-completed by households or carried out by smart meter installers with the households' consent.

Acknowledgements

This work has been carried out as part of the REFIT project ('Personalised Retrofit Decision Support Tools for UK Homes using Smart Home Technology', £1.5m, Grant Reference EP/K002457/1). REFIT is a consortium of three universities - Loughborough, Strathclyde and East Anglia - and ten industry stakeholders funded by the Engineering and Physical Sciences Research Council (EPSRC) under the Transforming Energy Demand in Buildings through Digital Innovation (BuildTEDDI) funding programme. For more information see: www.epsrc.ac.uk and www.refitsmarthomes.org

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From consumer smart monitoring to demand response in the domestic sector: Italian case studies

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Abstract

The contribution of households' electricity pattern loads into demand response logics is nowadays a crucial issue. However, one of the specific challenge is to increase the use of energy management technologies, as well as the market deployment of real time optimization of energy demand response intelligent building automation systems, balancing energy loads to reduce the peak power demand in homes. In this context, electricity consumption in the residential sector can be reduced by providing consumer with tailored information about their energy-using practices at home, also by using peer comparisons among clusters of user types. Moreover, when user engagement techniques are coupled with demand response logics, the benefit of such programs may exceed greatly. Final goal of the presented study is hence twofold. Firstly, by means *energy visualization and persuasive communication*, to endow domestic users to understand if their electricity loads are comparable to the typical consumption patterns identified among peer clustered families. Secondly, by means the implementation of *demand-response* logics, to manage more efficiently their electric energy loads at home. On the one hand, experimental data gathered from a smart monitoring in-home system installed in 31 homes in Italy, are used to evaluate global energy savings at the dwelling level. On the second hand, by means a dynamic demand response building energy model, the modulation of heating and cooling loads at home – for typical Italian household family types and climate locations – is simulated, in order to balance energy consumption and costs, without affecting household's comfort, habits, needs and routine.

1. Introduction

Although significant improvements in energy efficiency have been achieved in home appliances and lighting, the electricity consumption in the average EU-25 household has been increasing by about 2% per year during the last 10 years. Some of the reasons for such increase in the residential electricity consumption are associated with a higher degree of basic comfort and level of amenities (particularly in the new EU member countries) in addition with the widespread utilization of new types of energy intensive appliances whose market penetration and use has experience a very significant growth in recent years. The International Energy Agency (IEA) estimated that, even with a continuation of all existing appliance policy measures, the appliance electricity consumption will grow by 25% from 2000 to 2020 [1]. The introduction of energy labels, implemented with EU Directives for the last ten years, has produced a positive trend in the sales of more energy efficient appliances. Consumers have responded positively to this mandatory information scheme enabling comparison of respective energy-efficiency of various models in the same appliances family through appliances ranking into proper energy class (from A to G). The introduction of even better energy classes (A+ and A++) and the broadening range of appliances labeled are thought to produce even greater electricity savings. Nevertheless, due to technological limitations in further reduction in energy consumption, today's white goods and appliances have reached an asymptote in enhancement of energy efficiency. It is therefore clear that, to secure a sustainable energy development, attitudes and human behavior need to be modified towards a more efficient and conscious energy usage. In this view, user engagement towards more energy conscious consumption patterns can be seen as a driver of the future energy efficiency in the modern smart home energy system. Nowadays, consumption becomes an act of pleasure beyond satisfying basic needs: consequently, our changing lifestyle has dramatically impact on world energy demand. As a matter of fact, many serious worldwide problems accompany the increase of electricity use, such as global warming, urban heat island, environmental pollution, CO_2 emissions and degradation. Nevertheless, common citizen rarely care about these inconveniences and are often not aware that the energy amount they consume in their daily domestic activities is so closely related. Occupant behavior at home can enormously vary on the base of different energy related behavioral patterns: accordingly, studies in literature [2, 3] highlight that energy consumption in almost identical dwelling may increase up to a factor of 3.

Reducing energy-demand is hence an imperative issue, not only worldwide, but also at a household level is some way. In this context, results from domestic energy awareness campaign in Italy [4] and worldwide [5] demonstrate the energy saving potential of improving occupant behavior at home – e.g. by providing persuasive information techniques such as real-time and historical visualization of energy-use practices, energy reports using peer comparison logics and tailored feedback – is on the average among 15%. Moreover, advancements in metering industry are expanding the range of smart time-based monitoring tools such as in-home displays or home-area networks that can be offered to electricity domestic consumers to reduce peak period consumption from information on their typical energy-related consumption patterns at home. In this context, demand response programs allow domestic consumers to play an operation role in the electric grid and market, in order to lower energy bills and profit from derived energy savings. As stated by the Federal Energy Regulatory Commission [6], demand response (DR) can be defined as: "Changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized." On the one hand, such programs directly engage energy consumer to manage and shift their electricity loads during non-peak periods, in response to financial incentives, such as critical peak, variable peak and real time pricing, or time-of-use dependent rates.
On the second hand, with the deregulation of the electricity supply industry, the energy system occurs to reach the highest efficiency if fluctuations in demand are kept as small as possible [7].
Accordingly, demand response energy management supports electric system planners and energy providers in balancing supply and demand in wholesale markets, leading to lower electricity costs and retail rates, specifically deferring construction of new power plants and power delivery systems reserved for use during peak times. To do so, steadfast operation of the electricity system requires supply perfectly meets demand in real time. However, such optimum balance is not easy to attain, given the fast and stochastic variation of both energy production and consumption patterns. DR in the residential sector includes all planned or voluntary modifications to consumption patterns operate by domestic customers, engaged to adjust the timing, level of instantaneous demand, or the total electricity consumption of the appliances in their homes [8]. Engagements are normally undertaken in response to an economic signal (e.g. energy price, or government and/or utility incentive) but remain strongly contingent to personal preferences and lifestyles. Final goal of DR programs is to actively engage customers in modifying their consumption in response to pricing signals, while considering occupant behavior diversity, personal motivation and drivers to energy consumption change paradigms. Time-of-Use is mentioned in literature as the most convenient type of DR in the residential sector [9]. The basic idea is that customer participating in DR programs can expect savings in electricity bills if they reduce their energy usage during peak hours [10-12].
Three main actions exist by which such demand response program can be conducted.

1. A domestic user can reduce his/her electricity usage by shifting appliance usage from critical peak hours to off-peak periods. This shifting can be scheduled by the user itself at fixed time of the day, or automatically managed by a smart in-home controller, optimizing electricity supply from the grid at the cheapest time-based pricing, with the specific appliance power load demand in real time. In this scenario, the residential customer will bear no loss in terms of comfort, whether a proper decisional schema is set up beforehand in order to meet the household habits, needs and routine.
2. Electricity usage can be simply reduced by informing domestic users of peak hours when electricity price is higher. In this scenario, residential consumers are involved into a temporary loss of comfort, for instance because giving up in using a specific appliance, or changing the thermostat setting of heaters or air conditioners.
3. Customers generating their own power, i.e. integrating renewable electricity consumption produced by on-site PV panel to the energy purchased by the national grid. Such consumer/producer are often called "prosumer". This term was coined in 1980 by futurologist Alvin Toffler, to indicate consumers becoming "active" to personally improve services of the marketplace, hence transforming it and their roles as consumers. Prosumers have the highest degree of control over time-of-use demand response programs. Thanks to the buffer effect generated by their own electricity production, prosumer can mitigate the critical increase of energy cost during pick hours. In doing so, they can experience very little change in their consumption patterns ruled by households habits and routine, even managing to lower the demand usage from the utility perspective.

Many utilities and companies around the globe have experienced DR programs, reporting – on average – small reduction on the consumption demand side (5%) have resulted in around 50% electricity price during supply crisis [13]. This is due to the fact that electricity generation costs increase exponentially during maximum generation capacity. As a consequence, even small consumption reductions of the single domestic electricity consumer might result in significant cutbacks in terms of electricity prices.

2. Methodology

Assuming from literature studies that:

- electricity consumption in the Italian residential sector can be reduced by providing consumer with tailored information about their energy-using practices at home [4] and if households learn they use more energy than their similar, they will be motivated to reduce consumption and possibly use even less than their similar [14];
- when user engagement techniques are coupled with demand response logics, the benefit of such programs may exceed the cost by a factor of 7:1 [8];

final goal of the presented study is twofold.

1. by means *energy visualization and persuasive communication*, to endow domestic users to understand if their electricity loads is comparable to the typical consumption patterns identified among peer clustered families. To demonstrate this trend, experimental data coming smart monitoring in-home system connected to a customer interface are used to evaluate global energy savings at the dwelling level.
2. by means the implementation of *demand-response dynamic simulation models*, to manage more efficiently the heating and cooling electric loads at home, as a function of electricity cost.

Energy visualization and persuasive communication

As extensively presented in [4], quantitative electric power data were gathered during 10 months (October 2012 to November 2013) from a smart monitoring in-home system installed in 31 dwellings in Italy. Such System connected an electronic smart meter, 5 smart plugs associated to the main domestic equipment (dishwasher, oven, TV, refrigerator, pc) and a smart appliance (washing machine) to a Home Residential Gateway acting as the central coordinator of the entire Home Area Network and a Customer Interface allowing the resident to visualize and configure his/her energy behavior via computers, smart phones, tablets, in-house monitor and similar. In addition, qualitative information on household composition, family habits and type and number of electric equipment home installed were gathered in every dwelling via a web questionnaire. Rough monitored data coming from Smart Monitoring Interfaces were translated into information easy-to-understand from the user. Energy loads were visualized by users through the Customer Interface in terms of Key Performance Indicators (KPIs) of current electric consumption. Moreover, users were clustered based on their household composition and typical load profiles for each family type were defined. By means horizontal benchmarking methodologies, energy "saver", "average" or "intensive" user profiles, with reference to clusters of typical family household composition, were deduced. Hence, since it is demonstrated [4,5] that there is a social driver in the visualization of energy usage in comparative fashion, energy intensity profiles of users associated to the same family-type cluster were cross-compared between each other. Such feedbacks were sent via newsletters to users, involving users into an «energy-saving race» to boost a competition driving them towards more energy saving behavioral profiles at home. Finally, global energy savings evaluations were drawn.

Demand response dynamic simulation model

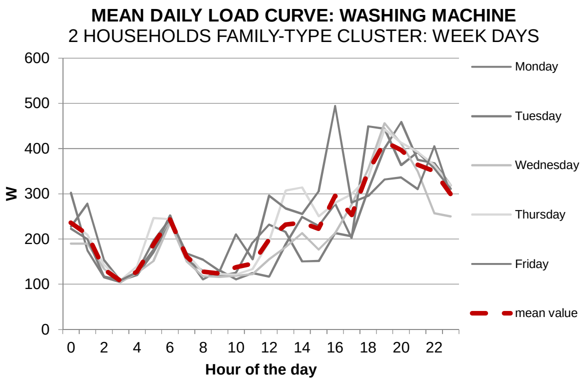
The second part of the study aimed at simulating the modulation of heating and cooling loads by balancing energy costs, maintaining indoor comfortable condition, as well as providing higher efficiency to the overall electric grid. An energy model of a singular dwelling was built using the dynamic simulation tool IDA ICE, in order to dynamically evaluate the feasibility of variations in a heat pump operation (heating and cooling schedules), the consequent indoor temperature ramps and the response in occupancy thermal comfort, as well as the impact on global energy consumption.
Two dwelling typologies were simulated in the study: a detached property and an apartment at an intermediate position in a building block. Their construction technologies were changed to represent three scenarios, representative of the Italian building stock, according to statistical data associated to the building construction age: 1965-74, 1975-91, after 1991 [15]. Temperature set points and schedules were first defined considering the standard comfort categories provided by the UNI EN 15251 [16]. Then, inputs were changed according to flexible prizing in electric energy market. Three different clusters of family type (working couple, 4 household family, and elderly couple) described the occupancy patterns. Simulations were carried on in three climatic zones representing North (Torino),

Center (Roma) and South (Palermo) Italy. The results were finally analyzed in terms of variation in energy consumption and costs, occupancy comfort feasibility and regional climatic differences.

3. Results

Energy visualization and persuasive communication

For each of the clustered household family-type users, electric power loads identifying typical daily consumption of singular home equipment usage (refrigerator, washing machine, dishwasher, oven and TV) were integrated over the 24 h of the weekdays and weekends. Hence, mean electrical consumption were drawn, corresponding to the mean daily electricity load curve of monitored families having same composition, and it was assumed as the *typical* domestic electricity use for the specific family cluster. An example of the main daily load curve for a washing machine during weekdays and weekend in a 2-members family type is presented in Figure 1.



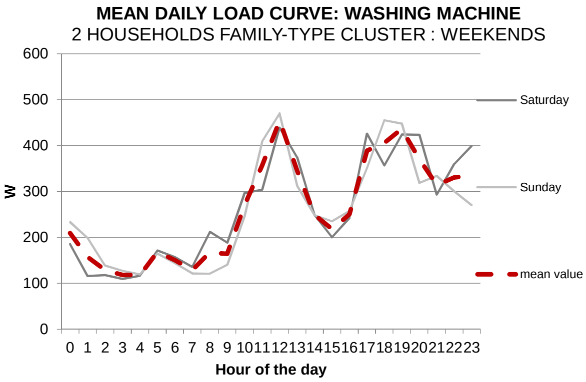


Figure 1. Mean daily electricity load curve of the smart washing machine during weekdays and weekends, for the clustered 2 households' family-type users.

A range of positive and negative values around the mean daily electricity load curves were settled as threshold values of a Buffer Acceptability Range (BAR) composed by three bands. The first band corresponded to the "average" consumption for a typical household profile. For every hour of the day, adding and subtracting the standard deviation to the mean daily load curves, let the settlement of upper and lower limits. Similarly, two more bands were defined to identify a range of "energy intensive" and "energy saver" behaviors. These two buffers were included between upper and lower limits of average ranges and threshold values identified as the standard deviation of minimum and maximum average value of electrical pattern loads (Figure 2).

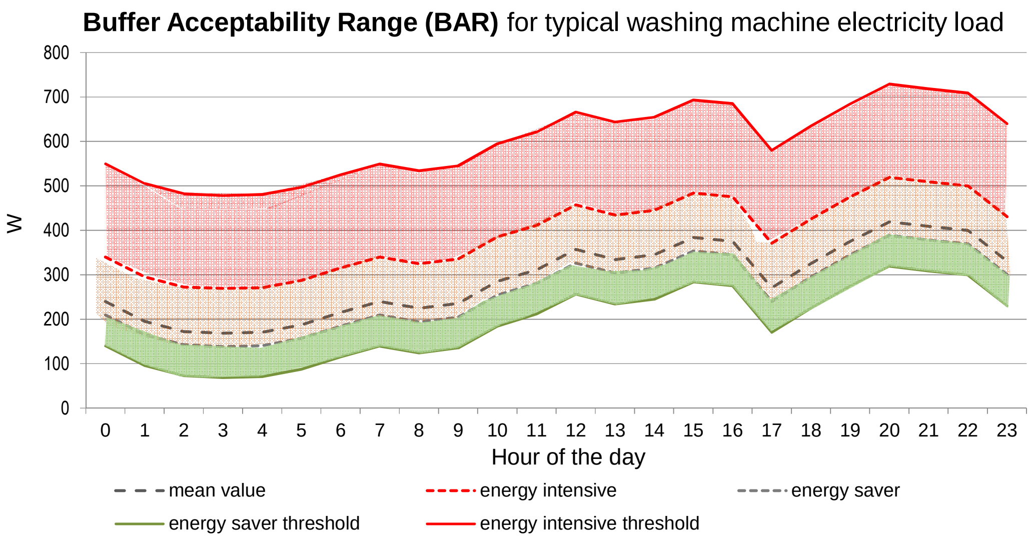


Figure 2. Buffer Acceptability Range (BAR) for the smart washing machine during weekdays, for the clustered 2 households' family user types.

The BAR was therefore used as self-reference benchmark for the average electric energy consumption of each specific family type. Daily average pattern loads of singular users were compared to the BAR of similar household's clusters. By doing so, the users' energy profile breakdown was targeted as "energy saver", "on the average", up to "energy intensive", both for general electricity consumption and electrical appliances (i.e. washing machine) home installed, during weekdays and weekend (Figure 3).

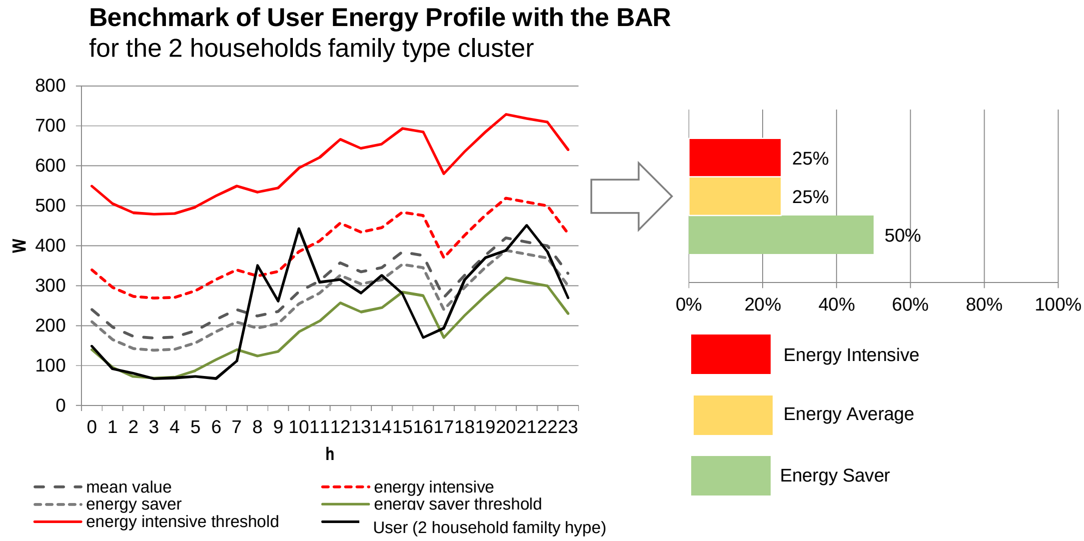


Figure 3. Comparison of a single user's smart washing machine mean daily electricity load curve to the corresponding 2 households' family type cluster's BAR and target of the user's energy profile.

Comparison between mean daily electricity load curves from the beginning to the end of the monitoring period was performed for each of the family type clusters. The calculated variation in electric consumption of every users belonging to the same cluster (i.e. for the washing machine usage), was shown in the same graph, both in terms of power loads usage (W) and savings (€). Such graph was send via mail to the users, so that similar households can compare their improvements and compete to gain the highest improvements, in a sort of «energy-saving race». The ideal goal of such energy visualization feedback was to lead similar families to have similar (and low) electric consumption, ideally reaching the finishing line in their energy race (Figure 4).

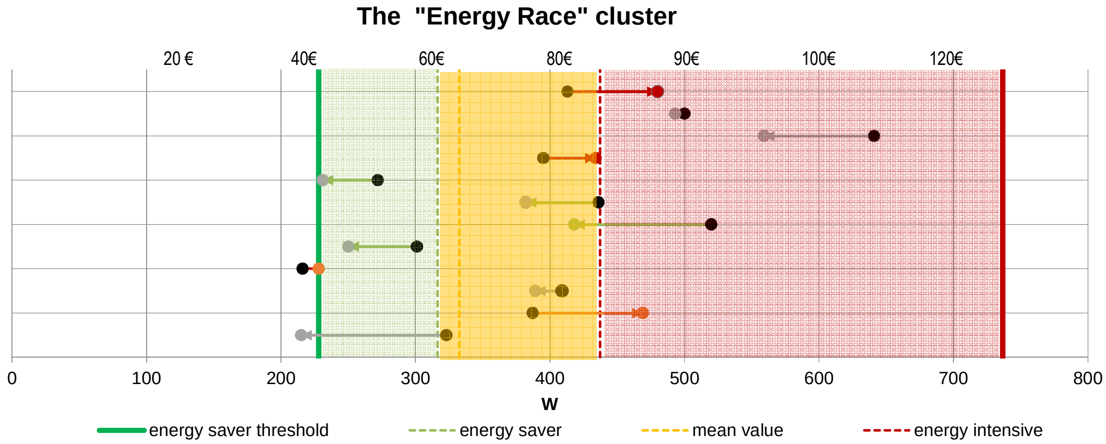


Figure 4. Washing machine "Energy-Saving Race": 2 households' family type cluster.

Results of the energy visualization and persuasive communication study demonstrated that more than 73% of the testing-users (23 over 31) achieved energy savings, after installing the Smart Monitoring System in their homes and receiving personalized information following a peer comparison "energy-race" fashion. On the average, reduced energy consumption emerged by 18% and this trend coherently confirms available studies in literature (Figure 5).

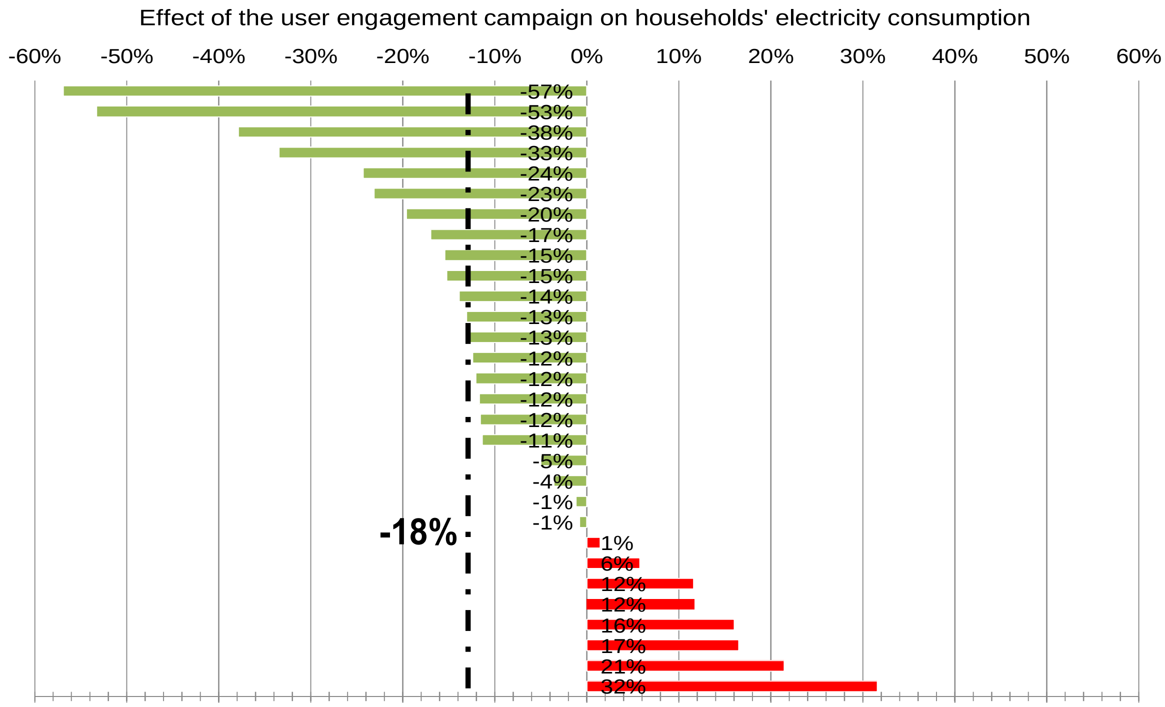


Figure 5. Variation in electricity consumption after the user engagement campaign conducted in 31 Italian dwellings having installed the Smart Monitoring in-home system.

Demand response dynamic simulation model

Results of the dynamic demand response simulation model for heat pump operation (heating and cooling) highlighted the effect of changing the schedules of temperature set points' on human comfort as a function of different clusters of family type occupancy patterns, building envelopes characteristics and outdoor climates. Simulations of the detached house model in Turin with three different building envelope and occupancy pattern configurations highlighted only slightly changes on temperature ramps in the different seasons. For instance, indoor temperature drop on average around 1°C in 13 minutes during summer and winter, while 15 minutes in autumn and spring. The apartment in an intermediate position of a building block represents a very different scenario: during the winter season, air temperature drop of 1°C occurs after 40 minutes in Turin (Figure 6) and around 50 minutes in Rome and Palermo.

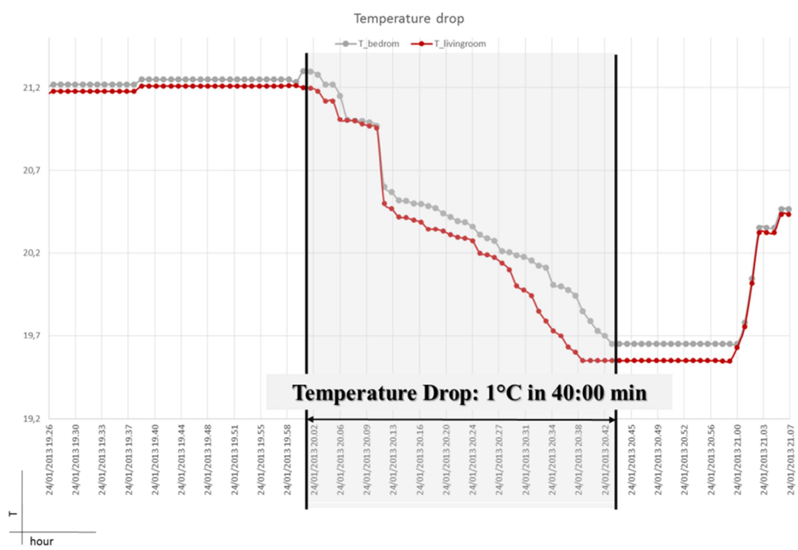


Figure 6. Temperature ramp due to flexible heat pump operation in a simulated apartment.

Based on these scenarios, the study on demand response analyzed the feasibility of using temperature control strategies that account of electricity power-peak periods to decrease or increase the temperature set points for heating and cooling. Accordingly, temperature ramps occur taking into consideration the time-event constraints defined by [17]. In the specific case, the benefit of implementing the demand response logic will result first in terms of energy balance, and secondly in terms of energy saving. The simulated domestic user can reduce the electricity usage for heating and cooling by decreasing the temperature set point of 1°C during peak hours. Energy consumption varies for the different occupancy patterns, and Italian climatic locations representing North (Torino), Center (Roma) and South (Palermo) Italy (Figure 7). This variation allows the shift of the heat pump usage from critical peak hours to off-peak periods, based on winter and summer temperature set points. In this scenario, the residential customer will bear no loss in terms of comfort, whether a proper decisional schema is set up beforehand in order to meet the different household clusters' occupancy, habits, needs and routine.

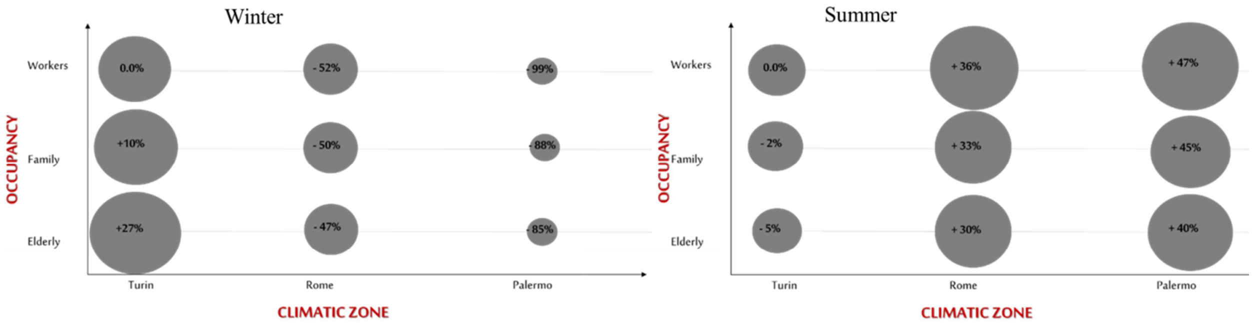


Figure 7. Simulated energy consumption for different climatic zones and family types, during winter and summer time.

4. Discussion and Conclusions

Assuming from literature studies that electricity consumption in the residential sector can be reduced by means energy visualization and persuasive communications, and when user engagement techniques are coupled with demand response logics, the benefit of such programs may be significant, goal of the presented study was twofold.

On the one hand, by means *energy visualization and persuasive communication*, to endow domestic users to understand if their electricity loads is comparable to the typical consumption patterns identified among peer clustered families.

Results of this study demonstrated that raising awareness in occupant's energy related behavior – by means visualization of domestic energy loads, personalized information of typical household consumption patterns, and peer comparison "energy-race" feedbacks – is effective in reducing electricity consumption on average by 18%.

On the second hand, by means the implementation of *demand-response* logics, to allow households to manage more efficiently their heating and cooling electric loads at home, maintaining indoor comfortable condition, reducing cost and providing higher efficiency to the overall electric grid.

Simulation results showed how it is possible to decrease the temperature set point of 1°C during peak hours by setting and changing the temperature set points and schedules in accordance to energy demand in a smart grid perspective. Nevertheless, respecting household's comfort, habits, needs and routine remains a quite stringent limit.

This study gave evidence to the fact that improved occupant behavior in building can be seen as a zero-cost (or low-cost) investment to enhance the energy saving potential in residential buildings. Indeed, simple and low cost solutions which can be provided to a large amount of people may provide a higher aggregated result than higher cost solutions provided to only a few (i.e. renovation packages in energy building retrofits).

Further developments in persuasive strategies and personalized energy feedback and demand response logics are required in order to identify the most efficient mechanism to empower households in energy saving. Improve customers' knowledge on energy saving opportunities in households is therefore crucial, with particular attention to electronic and ICT devices, their capacity to monitor and analyze the energy use information and to provide consumers with feedback and on the energy consumption of their appliances.

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Existing trade-offs between power capacity and energy efficiency increase in the age of systems

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Abstract

So far technologies have been mostly conceived as silver bullets entering seamlessly into everyday life without any subsidiary effect on other technologies and in general on ideas and practices. One of the consequences of this mindset is that energy analyses are typically performed by assessing the energy impact of single energy end-use technologies during their lifecycle without paying much attention to the effects of their interactions with other technologies and with the daily practices they are embedded in. Such an approach may lead to wrong estimates of technologies overall energy impact and often it does not allow identifying those cases in which energy efficiency improvements (EEI) boost higher energy consumption. This is particularly the case in the present historical situation when most of our daily activities rely on the employment of an increasing number of different energy consuming devices and when all these devices end up with becoming a system whose overall energy performances depends more on how all its energy using components interact than on the energy efficiency of each individual component. This paper aims to provide a series of insights concerning how EEI may affect the energy performances of technological systems. This is mostly done by drawing on complex adaptive systems theories whereby technologies are viewed both as elements of daily practices and nodes of a network of interconnected technologies where through energy, matter and information flow (e.g. refrigerators are viewed as part of practices related to eating, drinking, cooking, shopping, and as such linked by these practices to technologies used for food preparation, food conservation, food transportation, etc.). Besides presenting a different perspective to analyse EEI impacts, this paper illustrates the epistemological implications of considering technologies as part of larger complex systems and explains how the point of view proposed allow identifying in their power capacity increase one of the main drivers of complex systems evolution. By starting from this point, it finally discusses whether and how the energy impacts of these systems can be possibly optimized.

Introduction

The following sections aim to illustrate how an evolutionary perspective applied to networks of practices[1] and technologies can help better understand energy efficiency improvement (EEI) impacts in the age of systems. This objective is achieved in a series of subsequent steps. First of all the main characteristics of a system are described and the effects of the epistemological rupture that has determined the passage from the age of tools to the age of systems are generally analysed by focusing on the changes induced on the role played by technologies and human artefacts in everyday life. Some of the theories that seem to better reflect the epistemological assumptions of systems are then briefly described. Two phenomenological thermodynamics principles formalised in the framework of the complex adaptive systems (CAS) theory and their implications for systems power output and systems efficiency evolution are analysed in particular. Then, the challenges connected to long term and large scale evaluation of EEI impacts on systems evolution are briefly discussed. Finally, some general conclusions are drawn concerning how energy policy making could take systems dynamics into account in order to optimize the impact of technological systems on existing energy sources.

[1] The concept of *practice* has been precisely defined in the context of practice theory. According to this theory, practices consist of material elements (i.e. material, technologies and tangible, physical entities), image elements (domain of symbols and meanings) and skill elements (i.e. competence, know-how and techniques) which are linked together and co-evolve in the socio-technical milieu. Practices are assumed to come into existence, persist or disappear when links between these fundamental elements are made, sustained or broken. On this topic see for example [25], [30], [32].

From the age of tools to the age of systems

According to several scholars ([6]; [26]; [27]; [1]), a very important and often neglected epistemological rupture took place around the 1950s and concerned the way in which a large category of human artefacts named tools or instruments are conceived and perceived. Until the mid of the twentieth century, these artefacts were mostly perceived as means used or designed by human beings to achieve predefined ends, in the same way in which e.g. a typewriter can be seen as a device designed and used to print letters of the alphabet on a sheet of paper. While allowing achieving predefined ends, these tools were seen as objects which could embody human intentions and remain clearly detached from the body of the persons using them. This perceived separation or *distality* [6] between the tools and their users was at the roots of the separation between an objective reality and the subjects who know and act on it by using tools. On the other hand, it typically generated two contrasting views concerning the responsibility for the consequences of tools mediated actions. According to some people (probably the majority), it appeared indeed that tools could be employed by any person provided with sufficient skills and information background without affecting or redefining his or her intentions. For this reason, a kind of neutrality and objectivity was generally ascribed to them, whereas the full responsibility of the consequences of the actions they allowed to perform had to be attributed to the will of their users. For other people, this responsibility had instead to be entirely attributed to tools that appeared as able to deeply redefine human intentions with unexpected and often disastrous consequences for humans and their environment[2].These contrasting assumptions and perceptions, still largely present in contemporary society, have deeply influenced any field of knowledge and human activity since they entered diffusely the public discourse presumably around the XIIth century[3].

It was mainly because of the scientific progresses registered in the field of cybernetics [3] that a new epistemological approach to the interpretation of reality started spreading in Western countries in the twenties of the XXth century and culminated in the invention of computer technology and the discovery of the double helix structure of the DNA in the 1950s. The computer became the main metaphor for a new awareness of the world and of the *self* and the underlying theory of *systems* became the new reference point to re-conceptualise knowledge. In order to grasp the nature of *systems* and somehow overcome the abstractness of any definition that can be formulated, it may be helpful to think of neural networks or ecosystems as possible material representations of this concept. Strictly speaking the main characteristics of a system can be assumed to be those sketched by Gregory Bateson, one of the pioneers and fathers of cybernetics[4]. According to this anthropologist any system can be defined as an entity with at least the following six characteristics: (1) it as an aggregate of interacting parts or components whose (2) interaction is triggered by difference[5] thanks to the (3) consumption of some collateral energy. Moreover (4) it requires that circular (or more complex) chains of determination take place within it and (5) the effects of difference are to be regarded as transforms (i.e. coded versions) of the difference which preceded them. Finally (6) the description and classification of the processes of transformation taking place in a system discloses a hierarchy of logical types[6] immanent to phenomena. Generally speaking, a system can be considered as a self-corrective network of circuits where information and any associated material flow thanks to the consumption of some collateral energy. When an aggregate of interacting parts is seen as a system, its evolution is interpreted in terms of a series of incredibly complex feedback loops allowing to keep an *equilibrium* or *homeostasis* of information flows within it despite possible (minor or major) fluctuations in its boundary conditions

[2] The current debate on increasing access limitations to weapons for US citizens is an example of this dichotomous perception. Part of the public opinion attributes the responsibility for the increased number of murders being registered in US to the wide presences of weapons among US citizens. Another part (weapons manufacturers especially) maintains that the responsibility for murders has to be ascribed to the will of murderers and not to the weapons themselves.

[3]According to some scholars, the origin of the separation between body and tools dates back to the XIIth century [6]. The concept of tools as "*instrumenta separata*", as objects independent from the hand that holds them, was not very largely known before the twelfth century. These scholars affirm that, before this century, it was not possible to distinguish even linguistically between e.g. a hammer, a pencil or a sword and the hand that held them. The hand, the hammer and the hammering hand were all called *organon.* It is only after this century that a hammer can be seen as something made for hammering and the sword something for killing irrespective of the type of person using it.

[4] Bateson referred these characteristics to what he defined a "Mind". In the opinion of the authors of this paper the concepts of "Mind" and "System" overlap perfectly.

[5] The concept of "difference" was employed by Bateson as a synonymous of "information" that was defined by him as "a difference which makes a difference". According to Bateson the elementary unit of information is a difference which is able to generate a difference along the pathways of the system where it travels.

[6] Logical types were first defined by A.N. Whitehead and B. Russel in their "The Principia Mathematica" . See [4] for further information.

due to interactions with an ever changing environment. Thanks to these feedback loops, the system can keep constant the values of its internal parameters as happening for example with the temperature of a house where a thermostat and the feedback loops that this can activate allow keeping a constant indoor temperature despite outdoor temperature fluctuations. Systems are indeed supposed to be able to autonomously pursue their own ends. With them a new kind of teleology enters the scientific scenario and the Artistotelian *causa finalis* is readmitted to the scientific discourse after three centuries of hegemony exerted by the *causa efficiens*[7]. When the interaction between a person and a material object is described in terms of a system, the interacting parts can constitute a whole pursuing own ends. Systems can inscribe persons' intentionality into their workings. For example, Heinz von Förster [6] described a man walking a dog as a system with the man, the leash and the dog forming a unit processing informational signals that managed to make its way down the sidewalk. In the same way, the system made of a man interacting with a modern internet-connected computer can be described in terms of a two components unit processing signals to achieve own ends in the surrounding environment. The *distality* between user and object used that characterized the age of tools gets lost with systems. A man can still decide whether to use or to leave a hammer and the hammer remains the tool of a man as long as this hammer is conceived as an *instrumentum*. The system man-hammer is instead a kind of *cyborg* made of quasi-objects and quasi subjects, to use Bruno Latour terms[8]. Change and stability become the result of positive and negative information feedbacks which generate along system loops following environment perturbations and the distinction between action and reaction becomes often meaningless because circular causation loops are the only ontological entities of systems. At the same time, the body of persons becomes an *immune system* capable of keeping the value of its vital parameters (e.g. blood pressure, glycemic rate, etc.) within predefined variation ranges in a changing environment while body health is identified with a risk profile, i.e. a list of numbers representing the conditional probabilities that the measured values of its vital parameters may correspond to a system evolution towards a status threatening its own existence.
If the present age can be assumed to be the age of systems, this means that reality is being at the same time reinterpreted and rebuilt in the light of the above assumptions. Coming to the main objective of this paper, it is therefore useful and important to try to understand which are the implications of these assumptions for actions undertaken to improve energy performances of technologies which apparently have to be seen as parts of larger systems.

Some examples of how systems have changed human-practices and technologies

The fact that human action starts being driven by the ontology of systems has radical implications on how human activities are organised and on the role of human artefacts named technologies within society.
Some examples can perhaps help to better grasp the nature of this change. The first example relates to the transformation of the production processes organized according to a Fordian structure into a Post-Fordian structure [28]. Whereas a Fordian production structure is supposed to reflect a star structure where all the materials used to manufacture a given product converge to a centre, a Post-Fordian structure can be considered as an evolution of the Fordian structure and can be supposed to be better reflected by a structure like that represented in Figure 1.

[7] In his Metaphysics, Aristotle distinguishes among four kind of cause: *causa formalis*, *causa materialis*, *causa efficiens*, *causa finalis*. The difference among these can be grasped by the classical example of the sculptor. To make a statue the sculptor (causa efficiens) is supposed to produce changes in a block of marble (causa materials) with the aim of producing a beautiful object (causa finalis) having in mind his idea of the statue to be carved (causa formalis).
[8] See [14]

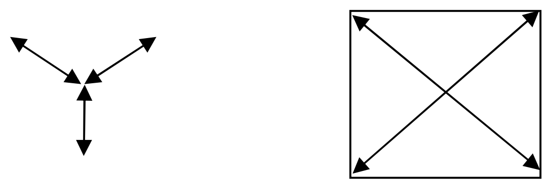

Figure 1: Paths reflecting a Fordian and a Post-Fordian production structure. Authors elaboration of graphs reported in [28].

In a Post-Fordian structure the production chain develops in production centres which are dispersed over the territory thanks to an improved transportation system for goods and each production centre can in principle provide its contribution to the final product by connecting itself to several different production centres. Ruzzenenti & Basosi [28] attribute this transformation to the free market competition supposed to have generated an outsourcing process whereby firms have externalized part or all of the production phases. This outsourcing process has indeed been at the basis of what they call a geographical gradient that has pushed some geographical areas to specialise in specific production intermediate processes. At the same time, production outsourcing has induced the creation of a series of additional and higher hierarchical levels needed to control the overall process and has changed the nature of the decisions to be taken and the parameters to be considered for production. Interestingly, the partial outsourcing of the production process represents a competitive advantage in so far as a given firm becomes able to choose among different production centres based e.g. on cost-benefit analyses, and this competitive advantage can be hence associated with the increased *connectivity* showed by the second graph reported under Figure 1. This increased competitiveness is in its turn associated with an increase in production system *complexity* and can be described in terms of a higher system *adaptability* because the increased number of connections that can potentially be established allows to maintain the production system "alive" by switching from a production centre to another in case the conditions for production change unexpectedly. Nevertheless, the externalization process at the basis of the dynamics illustrated above exposes the system to more uncontrollable factors (e.g. the free market forces) and determines a general loss of autonomy of system components. It is quite straightforward to identify the main characteristics of a system, including the six minimum requirements described in the previous section, in the example just illustrated. It is moreover worth mentioning that the increase in connectivity described above translates into an increased exchange rate of materials and information needed for production, which can be associated with an increase in energy consumption and has been possible thanks to the increased energy performances of the transportation system. This point will be further elaborated in the following paper sections.

A second example can be taken at a different scale by considering how practices related to food preparation and consumption have changed during the last 50-60 years in the households. It should not be difficult to realise how, also in this case, the process related to food preparation and consumption reflected more a star like structure when households mostly cultivated feeding products in their kitchen gardens and used more extensively their personal labour to cultivate, prepare and cook foods and to maintain all tools needed to these ends. Present food preparation and consumption practices are instead better reflected by a process structure similar to the one reported in Figure 2.

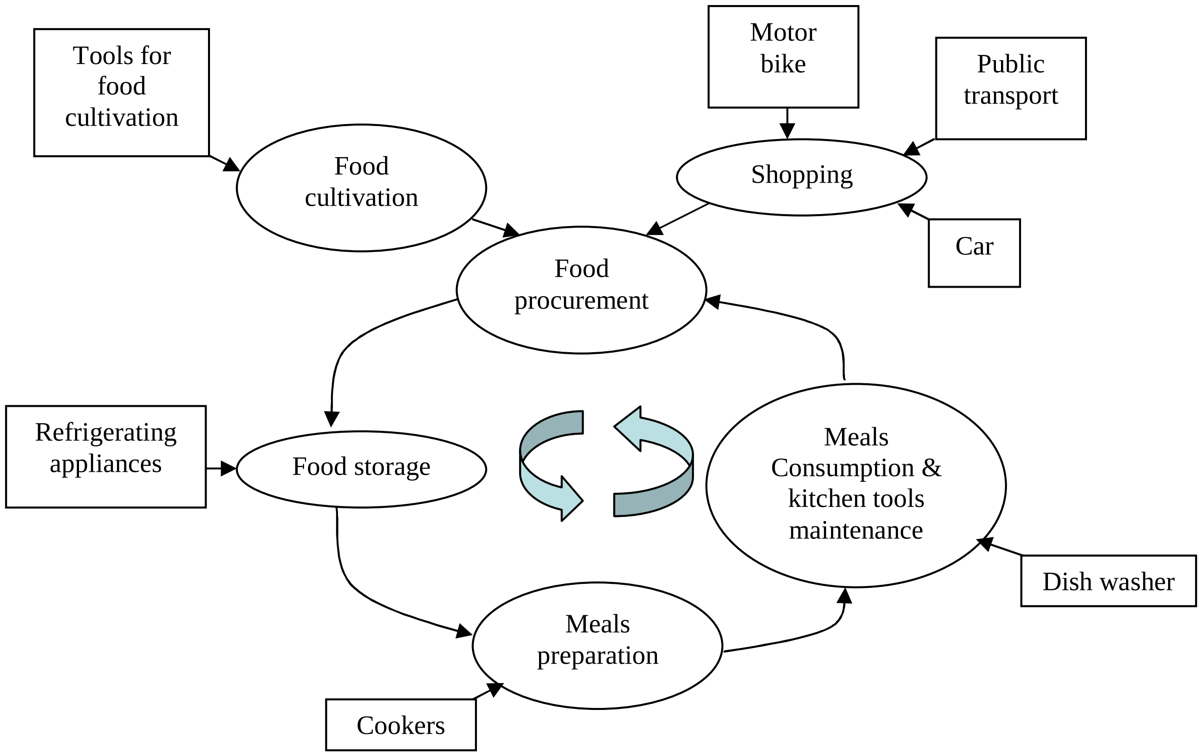

Figure 2: Some of the practices and technologies related to food preparation and consumption

The Figure 2 above is just a very simplified representation of the main present practices typically contributing to households food preparation and consumption (reported within rounded boxes) and some of the main energy consuming technologies (reported within rectangular boxes) contributing to the reproduction of these practices. When compared to practices of the recent past, the same transformations observed for the passage from a Fordian to a Post-Fordian production structure can be identified for this case. The outsourcing process at the basis of the industrial production structure transformation can be indeed identified with a progressively increasing *delegation* by households of the tasks to be accomplished for food preparation and consumption. This delegation has taken two different directions probably more clearly visible for the example of food preparation than for the example of the Fordian industrial process structure: on the one hand, this delegation has led to the involvement of an increasing number of persons in each (food) production process[9], while, on the other hand, it has implied a progressive substitution of human labour with work accomplished by machines consuming energy produced industrially. Both directions have progressively made households practices more *heteronomous* and have implied an increasing loss of control by single households on the production processes involved. However, these transformations have accelerated the production process and liberated a lot of time that households can decide to employ to perform other activities. As happened for the first example described, additional hierarchy levels have been created in the organization of this process and their introduction has progressively made households' food production and consumption more a question of *information* and *time* management than a question of manual activities to be accomplished. All in all, it should not be difficult to identify the transformation trends leading to the creation of a system fulfilling the minimum requirements sketched in the previous paper section also for this second case.

Another example can be provided even at the scale of single technologies with the forthcoming diffusion of so-called smart appliances which automatically turn on when the electricity is cheaper. Smart appliances represent indeed a striking example of how technologies tend to become part of systems integrating technologies and electricity supply networks. The intentionality of humans using these technologies becomes subordinated to information exchange loops that concern availability of energy at low price. These loops introduce complex additional hierarchy levels in the decision processes related to the usage of technologies, as happened in the examples previously described.

[9] Notice however that this does not necessarily imply that the total number of persons involved in *all* daily food production processes has increased.

It is generally worth highlighting that the passage from tools to systems implies a marked augmentation in the number of functions executed and practices reproduced by single material artefacts. As partly illustrated in the text above, this transformation can be represented in terms of an increased artefacts "connectivity". Rather than to tools conceived to achieve a specific end, this transformation makes single artefacts more similar to human prostheses whereby an increasing number of functions can be performed [9].

Theories reflecting the epistemological assumptions of systems

Besides cybernetics, the theories better reflecting the assumptions of systems' are probably those developed in the framework of complexity science and complex adaptive systems (CAS) in particular. Complex adaptive systems (CAS) are a relatively new research field developed mainly by researchers like Holland [10], Gell-Mann [8], Morowitz [18], Arthur [2]. The brain, the immune system, ant colonies, swarms, the internet and the human society itself are often presented as examples of CAS. Although encompassing different theoretical frameworks, CAS are usually described as large aggregates of highly interconnected and interdependent components delimited from the external environment by specific boundaries and operating under far from the equilibrium conditions. As such, the dynamics of these systems cannot neither be described by collections of linear equations, nor by the laws of equilibrium thermodynamics usually employed to explain the evolution of simpler systems. New CAS properties can indeed continuously emerge from interactions and information exchanges among their components and with the external environment. As also pointed out by Eidelson [33], these components are interconnected in a hierarchical manner in such a way that organization persists, grows over time and adapts to changing environmental conditions without centralized control. It is finally worth mentioning that the strong coupling among CAS components makes their evolution path dependent, i.e. what CAS can become in the future depends on what they have been in the past.
CAS theories generally rely on a representation of reality based on the concept of a network of interlinked biological and physical entities exchanging information and/or materials. All of them support an interpretation of technologies as both elements of daily practices and nodes of a network which are connected to other nodes of this network (i.e. to other technological devices) through these practices. In the following paper sections systems will be identified with the object of analysis of these theories to highlight systems' properties of relevance for the scopes of this paper.

The existing trade-off between power and efficiency within complex adaptive systems

According to a series of scholars, the evolution of CAS is regulated by two different principles depending on energy and time availability. Minimum entropy production or minimization of the input needed to obtain a given output are the expressions coined and most frequently used to refer to the first principle which dominates in a situation of energy scarcity and stable system boundary conditions. This phenomenological principle has been formalized by Prigogine [23], Glansdorff & Prigogine [7], Nicolis & Prigogine [19] for energy-dissipating systems in a steady non-equilibrium state and applies to systems which are close to the thermodynamic equilibrium. Broadly speaking, this principle implies that, in a condition of energy supply limitation and quite stable boundary conditions, system structures and components requiring a lower energy input to produce a given output have a competitive advantage and will prevail over less efficient ones (i.e. over system structures requiring more energy to produce a same output) determining a system reorganisation that can be characterized in terms of an increased system complexity. This reorganisation causes therefore a lowering in the diversity of options available to perform a same function in the short term and may put system survival at risk in case of a change in the boundary conditions. On the other hand, it diminishes system stress on the environment supplying energy and contributes to liberate energy whereby new structures can be created and contribute to successful system re-organisation in case a new situation of energy scarcity and new stable boundary conditions occurs in the long term.
The second principle has been instead formalized in terms of maximization of energy flows and has been proposed for the first time by Lotka [15]. Several names have been proposed for this principle by different scholars. It has been defined e.g. as "maximum power principle" by Odum & Pinkerton [20], as "maximum exergy degradation" by Morowitz [17], Jørgensen [12], Schneider & Kay [31]. It

establishes that in a situation of energy abundance and time scarcity CAS tend to increase the speed of energy intake in order to speed up the activity of existing structures and generate new structures. This enhanced diversity and intensification of the activities performed takes place at the expenses of system efficiency. The overall effect of the augmented energy intake is hence described in terms of a system growth and increased system power capacity accompanied by a decrease in system efficiency. The higher system power output may determine a higher stress on the environment and on the boundary conditions. On the other hand, the higher diversity achieved increases the possibility of a system reorganisation in case of significant systems boundary conditions change. System maximum power output corresponds to a status of higher diversity which is indeed a prerequisite for a higher system adaptability. This status enhances the chances of system survival through a system complexity leap whenever the conditions of energy resources scarcity and minimum entropy production are achieved.

Polimeni et al. [22] provide an example of household management to illustrate how the principles of efficiency and power output maximization co-operate in the evolution of CAS. According to them, economies made by families during routine activities comply with the above mentioned minimum entropy production principle and allow to save money amounts that can be subsequently reinvested in additional activities. What is saved at the lower level of routine metabolism can indeed be transformed into investments enhancing social interactions and create new activities at a higher level of household organization in accordance to the maximum power output principle. The final outcome of this co-operation process would be a better integration of families' metabolic systems with the environment during their evolution. Nevertheless, the reciprocal influence between efficiency and power output represents for Polimeni et al. [22] an overall drive toward instability. Systems evolution seems to be a question of eliminating the least energy efficient practices in order to be able to employ the available energy to generate more diversity whereby increasing adaptability in a context of continuously changing system boundary conditions. These authors underline that the goal of increasing diversity *per se* collides with the goal of increasing efficiency as defined at a particular point of space and time, although these two goals co-operate in the long term. Moreover, they point out that the phase of increasing diversity is a phase during which additional system outputs are generated and system efficiency cannot be properly defined. For example, they illustrate how energy efficiency improvements in cars have been associated with or have determined the introduction of new categories and variables in the formal identity of cars due to addition of many different gadgets and services and how this has represented an increase in the *diversity* of possible options available for consumers looking for a car[10]. It is only during the phase of resource scarcity and system reorganisation that an efficiency function can be defined and the different structural types can be mapped on this function in order to eliminate the least efficient and amplify the most efficient ones. Interestingly, these scholars consider identity redefinition as an intrinsic and fundamental property of systems that implies a continuous re-definition of what should be intended by systems output, systems power output, system efficiency and a continuous re-definition of the metrics that can be used to measure these quantities.

This important insight deserves further consideration. If the evolution of the technology of digital cameras is taken as example, it can be observed that when the first models of this new technology were put on the market increasing cameras' image resolution was the main objective of R&D activities and their output was therefore mainly assessed in terms of number of pixels/cm2. After a period of about ten years, digital cameras resolution grew exponentially and allowed in this way to generate new models with new functions and attributes. Consumers' interest in this parameter started decreasing and drifted towards the speed of sensors so determining what could be called a complexity leap. This triggered a new growth in the performance of digital cameras with respect to this parameter that became the new driver of the evolution of this technology generating in its turn new diversity and determining a dumping in the growth of their resolution. The definition of systems power output seems hence destined to change during system evolution and the same destiny seems therefore to be reserved to the definition of system efficiency (i.e. to the metrics employed to measure system outputs produced per unit of input consumed). Despite their continuous redefinition, efficiency and power of systems seem however to remain correlated as depicted by applying the thermodynamics principles briefly described above. It has to be pointed out that what allows power output increase during systems evolution is the peculiar nature of systems power output and the peculiar role played by *information* during system evolution. While evolving systems manage to increase their power output by

[10] Whereas e.g. speed and fuel consumption could be considered as the relevant parameters needed to assess cars performances during a certain phase of the evolution of this technology, subsequent energy efficiency improvements allowed to install air conditioners, four-wheel drive technology, etc. This increase of end-uses associated with cars has determined a change in cars identity requiring a different description and different parameters (e.g. related to how to measure efficiency of motors, efficiency of air conditioners, efficiency of four-wheel drive technology) to evaluate their performances.

continuously re-defining this parameter and this can happen only because the essence of systems power has the same material consistency of information. It is as systems would be endowed by an incredible level of vitality. Whenever the resource they consume to generate their outputs is abundant, they react by intensifying the activity of existing input-output structures and by generating new structures that can increase the possibility of system re-organisation and survival in conditions of resource scarcity[11]. This increased power output will be generally achieved in the long term by reducing the amount of material resources wherein this power output is generated, given the general scarcity of material resources typically available in the environment[12].

Ruzzenenti & Basosi [29] provide additional insights concerning the relation between efficiency and power in the evolution of systems by focusing on thermodynamic efficiency, i.e. the efficiency concerning conversion of heat into work. The existence of a trade-off and co-operation between thermodynamic efficiency and power is proved by these scholars by referring to the Carnot Cycle. This cycle proves indeed that maximum theoretical efficiency is achieved only under a condition of reversibility and infinitely slow speed (i.e. a condition of machine power approaching to zero). In order to get more than an infinitesimal amount of work and increase machine power, it is necessary to speed-up the process and consequently create a gradient between the temperature of the working substance and that of the heat reservoirs during the isothermal expansion and the isothermal compression of the Carnot cycle. This means that the two temperatures of the working substance during the isothermal transformations must be respectively higher than that of the cold reservoir and lower than that of the hot reservoir, i.e. the difference between the two temperatures of the working substance during the two isothermal transformations must be lower than that of the temperatures of the two reservoirs. The higher the gradients of temperature between working substance and reservoirs, the closer the two temperatures of the working substance during the isothermal transformations. When these two temperatures coincide, a condition of zero work and zero power is again achieved, because all the heat absorbed from one reservoir is transferred to the other without work generation. This reasoning demonstrates that the function representing the relation of machine power vs. efficiency for this Carnot model approaches zero at least two times, respectively when machine efficiency approaches the maximum theoretical efficiency and the zero value. Therefore, machine power must achieve a maximum in this efficiency range as schematically shown in Figure 3. This theoretical model is an exemplification of the trade-off between power and efficiency in CAS and how an increase of power output may be accompanied by a decrease in energy efficiency. Based on this model, Ruzzenenti & Basosi [29] conclude that in a situation of energy resource abundance CAS will tend to increase their power output at the expenses of their overall efficiency whenever time is a scarce resource, which is always the case in a context of species competition (i.e. in ecosystems) or in a context of economic competition (i.e. in human-made systems)[13]. It may be worth mentioning that all transformations which have led to the substitution of human labour with machine work can be considered as solutions elaborated to increase labour productivity (i.e. the output produced per unit of human time consumed) at the expenses of the overall efficiency of the production process[14].

The Carnot model used by Ruzzenenti & Basosi [29] can be employed to illustrate under which circumstances an increase of system power output can be obtained by increasing energy efficiency so reproducing the minimum entropy production principle[15]. This situation would results from any technical improvement concerning material improvement or friction reduction in the Carnot Engine parts leading to a faster heat transfer from the heat reservoirs to the working substance and would

[11] Clearly, the possibility of a system reorganisation cannot be established beforehand and a situation of resource scarcity may also determine the collapsing of the system.

[12] Computer technologies are probably the most relevant example of an increased power output (as measured e.g. in terms of bit/sec/cm2, or watt/cm2) involving a scaling towards small dimensions of components. It is worth mentioning that the *scaling* towards small dimensions which typically accompanies these exponential performance improvements can be analysed also in terms of energy performances (e.g. in terms of energy density measured as joule/sec/gr flowing through the system). This analysis shows that computer chips (probably the smallest existing technological devices) are the objects with the highest energy density in the universe [13]. They are therefore the most active and most evolved objects under the energy density point of view. The energy density ranking positions these artifacts respectively before airplanes, cars, the human brain, animals body, motors, plants, the earth, stars and galaxies. This record can ultimately be considered as the result of the progressively improved efficiency in the conversions of the energy inputs into the outputs of computer chips.

[13] This model describes increased power output only in terms of activity increase, whereas Polimeni et al. [22] maintain that power output increase is also due to the *emergence* of new structures and activities, as previously mentioned.

[14] As rightly reported by Ruzzenenti & Basosi [29], Jevons [11] maintained that "coal has never been more efficient or cheaper as an energy source compared to the sun. It was instead simply more economical in the sense that its usage was more fit for economy than the free, efficient, abundant, diffused and un-harnessed energy of the sun. A wind vessel has and will always be more efficient than an engine-powered boat. It is, however, the speed and most of all, the reliability of the shipment which marks the difference".

[15] It has to be highlighted that the link between energy efficiency and power output increase is established by the authors of this paper and not by Ruzzenenti and Basosi in the article mentioned.

correspond to a situation of increased system complexity (see Figure 3). Elsewhere the same scholars (see [28]) describe a situation of increased complexity as a situation when a new system organisation is established on a higher hierarchy level. This introduction of a new hierarchy would entail a coherent behaviour for lower level components.

All in all, CAS evolution would hence consist in a circular pattern whereby CAS grow and increase their power output and diversity (i.e. they add new activities and intensify existing ones at the same hierarchical level) while decreasing their overall energy efficiency as long as a condition of energy resources abundance persists. As soon as a situation of energy resource scarcity and system stress is achieved, a complexity leap corresponding to a system reorganisation and to an increased efficiency is realised in such a way that additional energy is liberated and the system can start growing again while increasing its diversity and power output. A recursive pattern that could then be depicted as growth-saturation-complexity leap-growth would hence be followed by systems. According to Ruzzenenti & Basosi [29] this pattern would not be necessarily established in case of efficiency improvements related to transformations from an energy type to another (e.g. heat or electricity generation), because these transformations do not necessarily entail the production of work[16]. In general, however the application of the Carnot model seems to indicate that energy efficiency improvements in situation of time scarcity are the necessary prerequisite for system and power growth, (measured e.g. according to the metrics of kWh/sec). Ruzzenenti & Basosi [29] support this conclusion by examples, illustrating e.g. how in the aftermath of the second oil crisis of the 1980 (i.e. in a situation of energy scarcity) efficiency of trucks in the EU was maximized while trucks power increased slightly. As energy prices started decreasing (i.e. as a situation of energy resources abundance was somehow re-established), trucks power started increasing significantly on average, while their efficiency started decreasing because of the higher average speed trucks were requested to achieve and of the additional functions they were requested to execute. At a larger scale the increase in truck efficiency would have been accompanied by a structural change from the Fordian production system to the post-Fordian production system characterised by a much higher frequency and distance of shipments as well as by a much higher system power output [29].

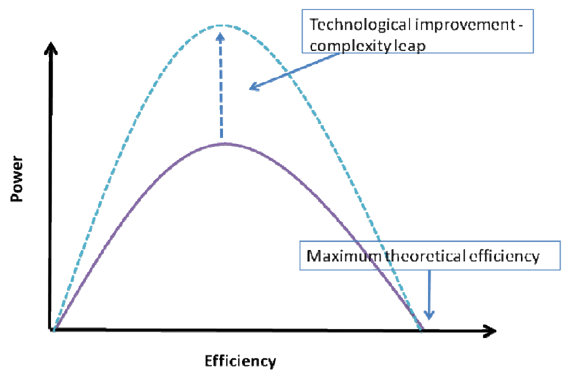

Figure 3: Simplified sketch of the efficiency-power trade off in a modified Carnot model as illustrated by Ruzzenenti & Basosi (2008b)

Phenomenologically, the power output increase seems to be the main driver of systems development (whatever system power output may be). On the other hand, an increased efficiency in the transformations of systems inputs into systems outputs seems to represent the necessary pre-requisite for system power output enhancements when the resource in term of which the system output rate is measured is scarce (either this resource is represented by time, or space, or bits, or Euros, etc.). When technologies become part of complex systems, technological development would become a particular case of complex systems development reflecting this phenomenological principle.

[16] In the opinion of the authors of this paper, this conclusion is not correct in so far as trasformed energy is and can be potentially used to perform different functions (e.g. domestic heat is used not only for space heating but also for DHW heating and other possible applications can in principle arise in the future). Also energy transformers can hence in principle create a structure and dissipate more energy.

Assessing systems' energy efficiency improvement impacts

The evolutionary perspective illustrated in the previous paper sections can provide some insights concerning the problems connected to long term and large scale evaluation of EEI impacts. While a series of very sophisticated techniques have been developed to assess EEI impacts in the short term and at the level of EEI impacts on the performances of single technologies, the assessment of these impacts in the long term and at large scale is characterised by at least the following challenges when technologies and human practices become systems[17]:

a) systems are open systems which are typically not in thermodynamic equilibrium
b) systems are hierarchically organized and operate on multiple spatial and temporal scales
c) systems evolve thanks to the establishment of circular causation/autocatalytic loops

Being open, systems exchange energy and matter and co-evolve with the environment. As also stated by Prigogine [24], this implies that systems are always "becoming" something else and makes any formal representation of their behaviour practically impossible. Considering that any assessment related to EEI impacts on systems' total energy consumption relies on a *ceteris paribus* hypothesis (i.e. on the hypothesis that everything but the EEI remains unchanged in a system), this introduces a large degree of uncertainty in the assessment. Any technological improvement can generally increase system activity level and determine a change in its formal identity by an expansion of the number of categories describing its outputs and activities, as illustrated in a previous section.

The impacts of systems' EEI on total energy consumption may change according to the spatial and temporal scales considered for the evaluation. It is indeed quite straightforward to understand that EEI impacts can even be reversed when impact assessments are performed at different hierarchical levels. Improving energy efficiency of cars and of mobility infrastructures in a given geographical area may for example result in less energy consumption attributed to each car during its lifetime, but may determine a higher energy consumption to be attributed to *all* cars circulating in that area because of an increased affluence to car mobility. Similarly EEI impacts for energy end-users may be different when assessed on a daily, monthly, annual or multi-annual basis. This happens for example when an EEI liberates energies that can be used to perform additional activities when accumulated over given thresholds.

Finally systems are by definition characterized by circular causation loops. This often makes the application of any reductionist model practically meaningless. In circular causation loops the direction of causation between two different events may change when assessed at different spatial or temporal scales, as in the famous "chicken and egg paradox". Polimeni et al. [22] explain, for example, that by looking at a single chicken it might be concluded that it is the chicken that makes the egg, but when the sequence egg-chicken-egg is considered, it should be concluded that it is the egg that makes the chicken to preserve itself. The creation of circular causation or autocatalytic loops are at the roots of any auto-organization process within systems and may make EEI impact assessment very tricky. Just to mention one example related to energy efficiency, the installation of efficient air conditioners made it possible to employ new and cheap construction technologies that would not otherwise have been able to guarantee acceptable comfort conditions in buildings of many countries in the world. The diffusion of these new and cheap construction technologies forced in its turn to install energy efficient air conditioners in an increasing number of newly constructed buildings often determining an overall dramatic increase in residential electricity consumption due to air conditioners. Can it be assumed that energy efficient air conditioners are responsible for the increase in the electricity consumption, or should the new construction technologies be considered responsible for this increase?

Efficiency-power and scarcity-diversity trade-offs

When the efficiency-power trade-off is analysed by paying attention to the implicit assumptions of the model whereby this trade-off can be observed, one finds that the efficiency-power or efficiency-diversity tension may have in principle different intensities depending on whether it is observed in a technological framework (i.e. it is observed in terms of *measured* efficiencies and *measured* power outputs) or not. This point can be grasped by focusing on the role played by the concept of *scarcity* in the above dynamics and on the assumptions determining the perception of a situation of scarcity.

[17] Most of the conclusions and considerations reported in this section have been formulated and described in more detail in Polimeni et al. [22].

According to CAS theory, systems' power growth is driven by two factors: 1) an increase of system *diversity* (corresponding to the creation of new structures) accompanied by the intensification of the activity level of existing structures in a situation of resource abundance and *time scarcity*; 2) a system re-organisation accompanied by a redefinition of system power output and an improvement of system efficiency in a situation of system *input resources scarcity*. The two necessary preconditions for the definition of these situations of scarcity within a technological environment are a) the operative definition of a physical quantity and related metrics to assess the number of available resource units and b) the establishment of a conservation principle for this physical quantity as assessed according to the defined metrics (e.g. the operative definition of time and of its metrics and the subsequent verification of a time conservation principle allow establishing that each person has 24 hours/day available; the operative definition of energy and of the related metrics and the observation of an energy conservation principle allow establishing that the amount of energy totally available is constant for an isolated system, etc.)[18]. Moreover, it has to be taken into account that the definition of a metrics for the power rate associated with a given activity implicitly produces a change of perception concerning the number of different ends/outputs that this activity allows to achieve and connects the output amount that can be generated to the consumption of a scarce resource. This can be easily grasped by observing for example how the assessment of a walk in terms of m/sec walked connects the travelled distance to time consumption. All the possible ends that can in principle be achieved by this activity (e.g. the possibility to meet other people while walking, the beneficial effects for the body, etc.) are in this way projected along the Cartesian axis associated with the defined activity power metrics (m/sec) and are subordinated to the value associated with this single unit of measurement when a technologically driven perspective is assumed. Considering that the metrics used to measure the activity's power rate (the seconds used to measure the speed of a walk) defines a condition of resource scarcity, people are generally eager to increase the activity's power output (the speed of a walk) for example by using a machine (a private car). This will surely produce a lot of benefits but will also typically decrease the efficiency of the performed activity (the energy consumed by a human being during a walk is generally much smaller than the energy consumed by a car to travel along a same distance) while increasing dramatically the amount of output produced (the amount of meters travelled by car). The most important point of this reasoning is that when the technological system producing the activity output will be somehow forced to perform a complexity leap (e.g. because system boundary conditions will favour the employment of public transport instead of private cars due to the higher energy efficiency of public transport compared to private cars) the different ends achieved by the initial activity (the possibility of meeting people, the possibility of enjoying physical benefits from the walk previously mentioned, etc.) will have a very reduced role to play in this leap. This somehow implies that, in any technological system evolution driven *only* by the maximisation of the production rate of *measurable* outputs or by the minimization in the exploitation of some *measurable* and *scarce* resource input for each produced output, the possibility for exploiting the potential of diversity represented by a huge number of ends achieved by the initial configuration will generally be very limited. It does not matter whether this happens because the “power” attributed to these ends is not measurable (e.g. because it is context dependent) or is voluntarily not taken into account. The ability for a system to adapt is significantly decreased just because its diversity potential is assessed in terms of an increase in the generation of standardised and measureable outputs in a condition of time scarcity. The relevance of this point should not be underestimated given that a condition of resource shortage can be achieved at very different rates depending on the diversity of functions performed and output types generated by consuming *each* resource unit (i.e. the higher the diversity, the later the resource shortage condition might be achieved). After all, if the diversity of outputs that can be consumed in the unit of time has an upper bound, the fact that more different outputs are generated per single resource unit consumed can result in a slowing down of the resource depletion rate. Also, it cannot be excluded that the associated perception of time scarcity can be reduced in this way.

The question is then whether and in which circumstances it can be possible and desirable to create the conditions to increase the diversity and the number of outputs generated by a technological system or equipment per *single* resource unit consumed in order to alleviate the burden on the resource system producing the flow of resource units consumed[19]. Clearly, this is a very general question involving a plethora of mostly contingent factors which are often very difficult or impossible to

[18] It may be worth mentioning that the definition of a metric to measure the availability of a given resource is also the necessary precondition to attribute an economic value to this resource and establish the well known type of resource scarcity based on the model of supply and demand.

[19] The reasoning presented here is based on a distinction among three elements: 1) resource systems producing a flow of resource units; 2) equipment and technological systems using these resource units; 3) outputs generated by these equipments and systems.

identify. One of these factors however can certainly be found in the type of rules established to administer the usage of equipments, of resource systems and resource units consumed. The influence of these rules on the generation of outputs diversity can indeed be hardly overestimated. Property rights on equipments and resource systems are for example just one of the aspects deserving particular attention when the necessity of increasing the number and the diversity of outputs generated by single resource units is at stake. As underlined by Ostrom [21] a series of very different rules may be established to give individuals rights to use particular types of equipment, to use a resource system at a particular time and place, or to withdraw a particular quantity of resource units. But even when particular rights for the resources used are unitized, quantified, and salable, the equipment and the resource system may still be owned *a)* in common by people, *b)* individually (according to competitive market settings) or *c)* by a central authority (e.g. the state). Central authorities make unitary decisions for equipments and resource system usage under the institutional setting *c)* or parcel out ownership rights to these goods and then allow individuals to pursue their own self-interests within a set of predefined property rights under the institutional setting *b)*. These institutional settings are particularly suitable to maximise the production rate of measurable and highly standardised outputs of technological systems and can prove effective in minimizing the associated *increase* of resource units' consumption. However, when it comes to produce a significant enhancement of technological systems adaptability without harming the specific resource system they rely on, the institutional setting *a)* has a very important role to play at least on a small-scale[20]. Self-governing and self-organised institutions whereby equipments and resource systems are owned and managed in common by people can indeed potentially generate a much higher diversity of solutions to employ available resource units and increase in this way technological systems adaptability while reducing their burden on the existing resource systems [21].

Conclusions and policy implications

Human-made artefacts are becoming systems. The implications of this transformation are that human activities and practices become more and more integrated into networks of technologies. These networks are hierarchically organised through information feedbacks loops and consume energy during their usage. Human agency is also deeply modifying as it becomes more and more integrated and distributed over an increasing number of different and interlaced material objects which reveal an increasing overall auto-organization capacity. One consequence of this trend is that the phenomenological theories developed to interpret the evolution of systems can be applied also to networks of technologies and practices. These theories (the CAS theory in particular) indicate that such networks evolve to maximise their power output by continuously redefining the nature of their outputs. Moreover, they show that, in a situation of resource abundance, a power output enhancement is achieved by increasing the system *diversity* (i.e. by generating new structures) and by intensifying the activity of the existing structures while the overall *efficiency* of the resource input-output transformation process results consequently decreased. On the contrary, when the resource employed to generate networks outputs become scarce, these networks reorganise by a complexity-leap by amplifying the most energy efficient structures and eliminating the least efficient ones in order to be able to continue maximising their power output. Overall, it has hence to be concluded that systems' power output is the main driver of systems' evolution and that the increasing of systems' efficiency is functional to power growth and to a better system integration into the environment. For this reason a sound balance between the degree of power growth and of energy efficiency improvement should always be achieved. Nevertheless, it should not be neglected that systems' diversity contributes essentially to systems adaptability in the long term and that the least efficient practices under given system boundary conditions may become the most efficient ones when boundary conditions change, as the first astronauts had to learn when they tried to use ballpoint pens in the absence of gravity and were obliged to return to the use of pencils[21]. When technology systems are analysed in terms of energy inputs, the big issue is then to understand whether it is possible to limit the total energy consumption they are responsible for. In the opinion of many experts this objective could be achieved by promoting energy efficiency and simultaneously curbing power growth. According to some of them an increase of the energy price and the “artificial” condition of energy scarcity created could be sufficient to achieve this end. According to others, EEI policy measures should instead be accompanied by measures limiting power growth directly (e.g. by limits to the speed or engines’ size in case the vehicles, by volume limits in case of refrigerators, by a minimum price set for bits/sec.

[20] Existing studies refer to resource systems located within a country and affecting a number of individuals varying from 50 to 15,000 persons [21].
[21] Example taken from [22].

transmitted by communication technologies, etc.)[22]. These two approaches however do not take into sufficient account the role that system diversity accompanying power growth plays for adaptability. Moreover, whereas the former approach may become questionable for the social equity issues connected to any energy price increase, the latter is often perceived as a limitation of individual freedom. This impasse can perhaps be overcome by a closer look at the specific nature of the diversity expressed by technological systems during their evolution (i.e. a diversity related to *measurable* system outputs and inputs). Increasing the energy efficiency of technological systems in order to reduce the impact on resource consumption of the increasing systems' power output is of paramount importance. On the other hand, the authors of this paper suspect that most of the approaches aiming at limiting or prohibiting systems' power growth and the accompanying technological development would be destined to fail when a perspective spanning a sufficiently large scale or long term is adopted. This, however does not mean that this growth cannot be somehow re-directed and systems' adaptability cannot be increased to avoid harming the existing stocks and funds of (energy) resources. Existing studies indicate that the development of institutional settings based on the self-organisation and self-governance of common technological equipments and resource systems have a very interesting role to play in this respect at least on the small-scale.

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Absolute energy savings in the household sector – a case for public policy?

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Abstract

The German Energy Concept, contains absolute energy savings targets as compared to a 2008 (or, for transport, 2005) baseline. The Ministry for Environment has commissioned the corresponding research project “Potentials, framework conditions and instruments for reaching the energy consumption targets of the Energy Concept.” It explores possibilities for reducing energy demand via behavior-related measures in private households, looking at the areas of housing, appliances, mobility and food This paper presents the approach and selected results from this ongoing project.

The project identifies priority measures and develops policy instruments in an iterative process including the following steps: 1. Selecting possible measures, 2. Quantifying savings potentials; 3. Assessing the ease of implementation of measures from a social science point of view; 4. Modeling economic costs and benefits and determining distributional effects; 5. Assessing existing coverage by policy instruments, and 6. Exploring new policy instruments.

A first result of the project is that most relevant efficiency potentials are already targeted by existing or planned policy measures. The remaining measures are, to a great extent, lifestyle changes and curtailment behaviour. The quantitative assessment shows that theoretically these measures could provide a substantial contribution to the savings targets of the Energy Concept, if broken down to the household sector. For example, 2020 primary energy and electricity savings targets could be reached by these measures alone. In addition, all of them have negative GHG abatement costs, meaning that they imply a financial gain. The social science and policy analysis show, however, that it is not easy to overcome the barriers to implementation of such measures.

The paper illustrates the process and results for three measures in the area of appliances: Reducing multiple appliance ownership, implementing absolute upper limits for appliance energy consumption, and curtailment-related usage behaviour. Also, three policy instruments are explored: a cap on electricity sales, life cycle cost information at the point of sale and a “scrap bonus” for old appliances. While the “scrap bonus” cannot be recommended and the LCC information instrument needs further development, the cap is a targeted instrument worth exploring.

Introduction: Policymaking, Efficiency, and Behaviour

When public policy addresses energy consumption in the household, two things are almost certain: it tends to focus on efficiency. And it tends to apply a limited concept of individual behaviour.

Energy efficiency policies abound. Efficiency is at the heart of the Ecodesign Directive[1], the Energy Labelling Directive[2], the Energy Efficiency Directive[3]. Energy efficiency appeals to policymakers because it appears to be a win-win strategy. Technically, it means improving the ratio between energy input (I) and performance[4] output (O): I/O. Its promise is therefore: More performance with the same

[1] Dir 2009/125/EU

[2] Dir 2010/30/EU

[3] Dir 2012/27/EU

[4] I use the term “performance” as a general term to cover a broad range of desired outcomes that are achieved via energy input. In industrial energy efficiency, performance could be measured by the number of products manufactured within a certain time. In end-use energy efficiency, it could be measured by the number of energy services provided, or by their extent and quality – e.g. room temperature, number of heated rooms, temperature of cooled food, amount of cooled food, time needed to achieve a certain desired temperature level, size or speed of a means of transport, size and functionality of a TV set, speed and performance of a computer etc.

energy input – or the same performance with less energy input. This, in turn, means cost savings, new markets for the more efficient products, competitiveness, jobs, and all of this without a sacrifice of performance.

However, there is just one flaw in efficiency. It is simple math: An improved I/O ratio cannot only be achieved by lowering I and keeping O constant, or by increasing O and keeping I constant. One can also increase O *a lot* and I just *a little bit*. This means: *much more* performance with just *some more* energy input. And this is what generally happened, in industrialized societies, with energy efficiency. [2]. On the individual product level, there was *much more* functionality, size, connectivity, or speed requiring just *some more* energy consumption. On the aggregate societal level, there was *much more* usage of products with just *some more* aggregated energy use.[5] In sum, impressive efficiency increases have done almost nothing to bring down overall energy consumption – in some sectors, quite to the contrary.[6] Public policy is hesitant to tackle these trends towards "more". Energy policy scenarios, even environmentally motivated ones, tend to treat them as given. Rising "activity rates" – meaning rising GDP, rising per capita living space, rising person-kilometers, rising levels of appliance ownership – are treated as external input parameters, and policy needs to work its way around them (see for example [7] and [8]. An exception is, with respect to the transport sector [9]).

However, even renewable energy is not infinite. Already today, conflicts over land use, landscape protection and power lines abound. The electrification of vehicles will increase the demand for electricity, exacerbating such conflicts. It is therefore reasonable to assume that a transition to a renewable-based energy system will require that total energy consumption goes down.[7] Historical experience indicates that this, in turn, will require more than just efficiency. It will require addressing the activity rates.

A second frequent feature of policies aiming at energy consumption in the household is their limited concept of individual behaviour. Policy scenarios mainly target investment behaviour – be it in the area of housing (efficient heating, insulation) or efficient appliances [7], [8], [9], [16]. Then, there is a certain subset of usage behaviours that comes into the focus of policy from time to time –such as switching off appliances when not using them, avoiding standby, or turning down room temperature. This, in turn, is understood as basically a personal choice, depending on preferences. Consequently the range of policy instruments that could legitimately influence it appears limited. Dramatic price increases or regulatory policy are generally not considered viable options, and sophisticated psychological interventions such as team-based approaches or goal setting are difficult to implement on a large scale. Therefore, discussions center mainly around awareness campaigns and feedback mechanisms. (See, for example, [10], [11], [12]).

However, individual behaviour can do more. Reaping its potentials requires both a broader concept of what individual behaviour is and comprises, and a clearer picture of its dynamics, antecedents and barriers. This would in turn lead to a better understanding of the role of policy in shaping it, and possibly a broader range of policy options.

This paper presents first results of a project that is different in both respects sketched above. Instead of focusing on efficiency, its aim is to help bring down household energy demand in absolute terms. In pursuit of this aim, it does not shy away from tackling "activity rates". Instead of looking at investment behaviour and selected usage behaviours alone, it applies a broad concept of individual behaviour and tries to develop an understanding of the various ways in which it is embedded and shaped. The final goal is to inform public policy and develop adequate levers to help achieve energy savings goals.

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[5] This is an empirical observation whose causes are difficult to untangle. Part of this development is certainly due to the various types of "rebound effects", meaning that the efficiency improvement itself is the cause of the increase in output. Another part is due to autonomous technological development, economic growth or, in the past, population growth. Especially in the case of "macro-economic" rebound, rebound effects and autonomous growth are not always easy to distinguish, and few authors have tried to do so. (For literature overviews and critical discussions of the size and nature of rebound effects and their role in policy, see, for example,[3], [4], [5]; [6]).

[6] An impressive example is the development of lighting in the UK. While lighting efficiency increased 1000-fold between the years 1800 and 2000, per capita consumption (measured in lumen hours) increased 6500-fold. Because of population growth, total national consumption increased even 25,000-fold [1].

[7] Indeed, this is generally assumed in scenarios targeted at achieving climate mitigation goals, such as [7], [8], and [9].

Structure of the Paper

In the following, a short outline of the project and its political background will be given, highlighting its specific features and describing its approach. Afterwards, an overview of core results is provided in two sections: first, a set of potential energy saving measures with their evaluation from various disciplinary perspectives. Secondly, the potential contribution of the estimated savings potentials to the goals of the German Energy Concept. The remainder of the paper is dedicated to an exemplary illustration of the analytical steps and results, using the example of electric appliances.

Concept for the Absolute Reduction of Energy Consumption: An Outline of the Project

In September 2010, the German federal government published the cornerstones of its Energy Concept [13]. It contains a number of energy saving goals for 2020 and 2050. Rare enough, the goals do not relate to a “business as usual” scenario, but to a fixed base year (2008, or, in the mobility sector 2005). That is, energy consumption in the target years must be a certain percentage *below base year consumption*, regardless of what the BAU scenario for the target year would have been.[8] Table 1 gives an overview of the targets.

Table 1: Energy saving targets of the German Energy Concept

	Primary Energy	**Buildings**		**Electricity**	**Transport**
		Heat demand	**Primary Energy**		**Final Energy**
Base year	**2008**	**2008**	**2008**	**2008**	**2005**
2020 goal	-20%	-20%	--	-10%	-10%
2050 goal	-50%	--	ca. -80%	-25%	-40%

Sources: [13], [14]

In March 2013, the German Ministry of the Environment commissioned a research project entitled „Concept for the absolute reduction of energy consumption. Potentials, framework conditions and instruments for reaching the energy consumption targets of the Energy Concept.” [15]. The 2.5-year project is supervised by the Federal Environmental Agency (Umweltbundesamt) and run by Oeko-Institut e.V. and IREES GmbH. Its aim is to explore the energy saving potentials of behavioural measures in the household sector and propose policies for reaping these potentials in order to reach the targets of the Energy Concept. The special features of this project are:

- It covers a broad range of need areas;
- It applies a broad concept of energy-relevant behaviour and its antecedents;
- In an interdisciplinary approach, the analysis integrates different aspects that are relevant for judging the appropriateness and feasibility of energy saving measures and policies. The approach is expressed in the various project steps as presented below.

Need areas

The project covers the need areas of housing, appliances, mobility, and food. Although the present paper focuses on appliances (and to some degree, housing), highest saving potentials and most effective policy instruments have in fact been identified in the areas of housing and mobility.

Concept of energy-relevant behaviour

The project covers a broad range of behaviours, structured as follows:

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[8] Fixed baseline goals may not always be positive. For example, they may be reached by way of economic recession, without any additionality. However, persistent economic recession between 2005 and 2020 or 2050 is an unlikely scenario. The advantage of fixed baseline goals is that they are unambiguous and mean a definite reduction (and not only a smaller increase) of energy consumption which is desirable from a climate protection point of view. Of course, future updates may be necessary as for any goal.

- **Investment behaviour:** The typical feature of this type is that it requires a one-time effort that can be considerable. It involves conscious decision making, a weighing of costs and benefits, and transaction costs. However, once the investment is made, it will have a lasting effort on future energy consumption. If the investment has been chosen wisely, savings will come about “automatically”. Typically investment is conceived as financial investment, for example renovation of a building or purchase of an efficient appliance. This project also considers other types of behaviour that are similar in structure even if they do not involve monetary costs. For example, people may dispose of their private car or of an appliance, or they could move to another apartment that is smaller or better insulated. The former could be described as de-investment, the latter as immaterial investment (as time and effort is invested). All of these decisions are one-time decisions that shape future energy consumption in important ways,

- **Usage behaviour:** This type of behaviour consists of everyday patterns in the usage of energy consuming devices. It is usually highly routinized and not consciously reflected. Contrary to investment behaviour, the change of an individual instance of the behaviour usually does not require much (financial or mental) effort. On the other hand, to achieve energy savings, the behaviour must be kept up continuously. This requires constant attention and / or the changing of routines which are both psychologically difficult. Typical examples for energy saving usage behaviour are: walking or bicycling, lowering room temperature, filling the washing machine completely, or switching off lights and appliances when not using them. This project specifically considers sufficiency-related usage behaviours, as described below.

- **Lifestyle changes:** Contrary to investment and some usage behaviours, energy saving lifestyle changes are not often considered in policy scenarios. The project defines them as wide-ranging changes in a number of different areas of life that interact and influence each other. Examples would be the choice of one’s place of residence or the decision to move in with other people. Lifestyle changes can also be triggered by a single (de-)investment choice. For example, the decision to live without a private car has an impact on choice of place of residence, organization of the daily chores and holidays etc.

Furthermore, a distinction is made that cuts across these types: the distinction between efficiency and sufficiency (curtailment). While efficiency means, as described above, improving the ratio between energy input and service output, sufficiency means deliberately doing without certain services (functions, uses).[9] Or, in the language of energy scenarios, reducing activity rates. Both efficiency and sufficiency can take the form of (de-)investment behaviour or usage behaviour. However the distinction is somewhat blurred for lifestyle changes, as they by definition involve different aspects. Examples for the different types of behaviour are given in Table 2.

Table 2: Examples for types of behaviour

<table>
<tr><th></th><th>Efficiency</th><th>Sufficiency</th></tr>
<tr><td>Investment (including de-investment and immaterial investment)</td><td>Purchasing efficient appliances
Energetic renovation of a building</td><td>Disposing of the private car
Disposing of secondary appliances
Moving to a smaller appartment</td></tr>
<tr><td>Usage</td><td>Matching size of pan and cooking plate
Turning down heating if not at home
Fuel saving driving style</td><td>Watching less TV
Drying clothes on a clothesline
Walking or cycling
Taking cold showers</td></tr>
<tr><td rowspan="2">Lifestyle change</td><td></td><td>Entirely vegetarian or vegan diet</td></tr>
<tr><td colspan="2">Choice of place of residence; sharing a flat / house</td></tr>
</table>

Source: Author’s own

[9] The characterization of a certain behaviour as efficiency or sufficiency is not always straightforward, and also depends on the definition of “service”. For example, if the only “service” considered in eating would be the intake of a certain amount of calories, a vegetarian diet would not count as sufficiency. If, however, aspects such as taste or tradition are considered to be part of the service, vegetarianism would be sufficiency. In spite of these difficulties, we consider the distinction as analytically useful because it highlights specific policy challenges. A pragmatic approach at making the distinction empirically valid would be to ask whether a majority of respondents consider a certain change as a relevant change in service.

Project steps

The project applies an interdisciplinary approach including the following steps:

1. **Selection of promising energy saving measures**. The goal of this step was to reduce the number of possible energy savings measures to a subset that could be investigated in more depth in the following steps. An energy saving measure was defined as an activity that directly causes energy savings (e.g. renovating a house). In this, it is different from a policy instrument, which is an intervention to promote a measure (e.g. a subsidy program for renovations). About one hundred potential measures in the different need areas were collected from the literature. A pre-screening was then applied: Based on a literature review and expert judgment, the measures were preliminarily ranked on the dimensions that would later be analysed in depth: savings potential (see step 2 below), ease of implementation from a behavioural science point of view (see step 3 below), evaluation of cost-benefit relation and distributional impacts (see step 4 below), degree to which the measure has already been addressed by current policies (see step 5 below) and ease of political instrumentation (see steps 2 and 6 below). A preliminary list of 18[10] promising measures was created that met certain minimum requirements. Future steps applied to these measures led to the elimination of some more measures (see Step 2 and Table 3 for details).

2. **Assessment of energy saving potentials**. The goal of this step was to get a rough idea of the size of potential savings that could be generated by a measure. Savings were defined as percentaged reductions of base year consumption; with base years 2005 or 2008, as in the Energy Concept. Other than in the Energy Concept however, target years were 2020 and 2030 because a reliable assessment up to 2050 was not considered feasible. The assessment was conducted against an existing climate policy scenario that is used in German policymaking, the so-called "Energiewende" ("energy turnaround") scenario (EWS) in the study "Policy scenarios for climate protection VI", (PSz VI) [16]. This scenario already foresees reductions in absolute energy consumption in the household sector in 2020 and 2030, as compared to 2008.[11] In the present project, only *additional* savings as compared to the EWS were considered. As a consequence, it turned out that the typical efficiency measures that require financial investment (upper left cell of Table 2) were already covered by the EWS. Consequently, the present project focuses on sufficiency measures (de-investment, sufficiency-related usage behaviour) and lifestyle changes. Methodologically, the assessment was done via a literature review where possible. However, own projections where necessary in many cases because the literature used different baselines or operationalizations of measures. Methods used for the projections differed with respect to each measure and will be described in more detail in the examples below.

3. **Evaluation from a behavioural science point of view**. The aim of this step was to evaluate, with the help of knowledge from behavioural sciences, how likely it would be that individuals implement the selected measures. To put it another way, it was asked how much facilitation, incentive, "nudge" or even coercion from policymakers would be needed to have the measures implemented on a large scale. To this purpose, theoretical models of environmental behaviour were reviewed, as well as 64 empirical studies of pro-environmental behaviour in the various need areas. The aim was to identify variables, framework conditions, barriers and supporting factors that influence specific behaviours. From this body of evidence, conclusions were drawn for the implementability of the selected measures.

4. **Economic evaluation**. This step aimed at evaluating whether the selected measures are favorable from a cost-benefit and distributional point of view. Greenhouse gas abatement costs were calculated for twelve of the 18 selected measures that appeared promising after Step 2

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[10] In addition, a set of organizational measures that could be implemented in schools or workplaces was considered, but not followed up upon.

[11] The following savings are projected in the EWS: Space heating and hot water: -12% in 2020, -34% in 2030; electricity: -22TWh in 20020, -33 TWh in 2030 [8].

and Step 3 analysis and for which sufficient data were available.[12] In addition, for selected measures where distributional effects on specific categories of households (e.g. with respect to income, age, or family status) could be expected, these effects were assessed on the basis of a representative data set on household consumption, the "Income and Consumption Sample".

5. **Evaluation of existing policy instruments**. The aim of this step was to find out to what degree policies are already in place that help promote the chosen measures, and what gaps in the instrumentation exist. Twelve priority measures – three per need area – were chosen, based on the previous steps. A desk study was conducted to identify the policy instruments that were already implemented in each need area, and affected these energy saving measures intentionally or unintentionally. Selected instruments were evaluated with the help of the "intervention logic" approach [17]. This approach reconstructs the assumptions about causal chains that underlie a policy instrument, and checks internal coherence as well as empirical validity of the assumptions and the presence of necessary preconditions. Based on this exercise, a deficit analysis was conducted to identify whether and in which respect the selected measures are currently under-addressed.

6. **Proposal of new policy instruments.** This step aimed at developing new instruments that could promote the implementation of the selected measures more effectively. Ongoing political discussions and proposals in the literature were scanned for suggestions of new instruments. In addition, own suggestions were developed. All suggestions were subject to an ex-ante evaluation of effectiveness, efficiency, and consistency with the existing set of instruments, using again the intervention logic approach.

7. **Roadmap for policymaking.** All results will be edited to form a concise and consistent roadmap for future policymaking. This step is still outstanding.

Overview of measures

Table 3 gives an overview of the measures in the need areas of housing and appliances that have been followed up upon at least until step 2.[13] Not all steps have been conducted for all measures for different reasons (the most relevant being lack of data and focus on most promising measures). Steps that have not been conducted for a certain measure have been greyed out.

The table lists summary titles for the individual measures; detailed specifications and operationalizations will be given by way of example in the sections below. In the following, some further hints are given for the understanding of specific columns of Table 3:

The columns under "Step 2" give estimated annual final energy savings of each measure. The baseline is 2008 energy consumption. It is furthermore assumed that the policies described in the EWS scenario [16] will be in place, and only additional savings are calculated. In other words, if 2020 consumption is X TWh lower than 2008 consumption with EWS measures implemented, it will be another Y TWh lower if the measures considered in this project are also implemented.

The column "Step 3" gives the summary result of the behavioural science assessment. The measures have been ranked on a scale from 1 to 3, with 3 meaning most easy to implement. In the assessment, the possibilities to promote the measures via policy instruments are taken into account. That is, a "1" rating means that it is very unlikely that the measure can be implemented on a sufficient scale to reap the potential, even via policy instruments (for example, because no policy instruments are known that address the measure successfully, or because it is very unlikely that they will be implemented, e.g. for

[12] However, no full cost-benefit analysis was done because of the non-investive nature of the measures, so that they involved no monetary costs.

[13] The following measures were in the original list of 18 but have not been followed: M4 "Investing in thermostats", M6 "Investing in highly efficient circulators" (no additional savings as compared to BAU), M8 "Investing in highly efficient appliances" (no additional savings as compared to the Policy Scenarios"); M9: Low-investment measures (e.g. timers, lighting, switchable connector strips): for lighting, no additional savings as compared to the EWS; lack of reliable data for the other measures; M12b: efficiency-related changes in usage behaviour (no reliable data). Furthermore, measures in the need areas of mobility and food are not listed.

legal or acceptance reasons). A “3” means that people tend to realize this measure anyway, so that very little political intervention is needed, or that policies which successfully promote the measure can easily be implemented. An intermediate rating of “2” means that there are some or even considerable obstacles to the measure, but that it is imaginable that they can be removed by policies to a certain degree.

The columns “GHG abatement costs” under “Step 4” give the greenhouse gas abatement costs of the measure for 2020 and 2030. The costs are calculated from an individual perspective – meaning that monetary costs and benefits include taxes and fees, which would be disregarded from a societal point of view. All values are negative, meaning that all analyzed measures provide a financial benefit. For electricity, values are given for two scenarios: In the basic scenario, the average fuel mix is assumed for the saved electricity. In the sensitivity scenario, the fuel mix of the marginal power plants is assumed. It may strike the reader as odd that all measures in the field of appliances have the same abatement costs in EUR/t CO_2e. This is because none of the measures requires any financial investment, so only the positive side of the balance, the energy savings, remain. In addition, the saved fuel is always electricity (while for the other measures, there are different fuel mixes). With the fuel always being the same, the relation of “CO_2e/unit of fuel” is also the same, as well as the relation “EUR/unit of fuel saved”. Consequently, the relation “EUR/CO_2e” is also constant.

The column “Distributional effects” under “Step 4”gives a qualitative account of the results of the analysis of distributional effects. More detailed quantitative accounts will be available in the project report [15]. For capacity reasons, this analysis could only be conducted for the measures with the highest savings potential in each need area. The column gives the results for relative and absolute savings, with “relative” meaning relative to the overall consumption of the respective fuel.

The column “Step 5” lists the existing instruments that could, intentionally or as a side effect, promote the measures. The column “Step 6” contains the suggestions for new instruments that have been collected in the literature. Instruments that have been analyzed in depth are marked in bold. .

Table 3: Overview of measures analyzed

	Type of behaviour	Step 2		Step 3	Step 4			Step 5	Step 6
		Savings		Ease of imple-men-tation	GHG abatement cost (EUR (2010) / t CO_2e)		Distributional effects	Existing policies	Proposed policies
Measure		**2020**	**2030**		**2020**	**2030**			
Housing									
1a: Freezing of per capita living space at 42m²	Lifestyle	-	13.3 TWh/a (47.9 PJ)	2	-	- 604.3		Energy tax, VAT, real estate tax, ETS (European Emissions trading system)	**"One stop shop" to support elder citi-zens in moving to smaller flats**, **subsidy programme for con-verting bigger resi-dences into smaller ones,** changes in communal planning law, various **tax disin-centives for bigger living areas**
1b: Reduction of per capita living space to 40m²	Lifestyle	-	37.3 TWh/a (135.7 PJ)		-	-604.0	Relative savings highest for: - higher income HH - Singles and child-less couples - pensioners, public servants, and the self-employed		
2: Reduction of hot water consumption	Investment / usage; sufficiency / efficiency	5.96 TWh/a (2.5 PJ/a)	9.55 TWh/a (34.4 PJ)	2	-393.6	-584.5		Electricity advice program for dis-advantaged HH, energy advice program, energy tax, electricity tax, VAT, ETS	Specific subsidy pro-grammes to support technical measures; extension of existing advice programmes, detailed hot water bill
3: Lowering room tem-perature by 1 degree	Usage, suf-ficiency	24 TWh/a (86.4 PJ)	15 TWh/a (54 PJ)	1	-440.7	-603.2	Relative savings are equal for all HH. Absolute savings are highest for - high income HH - families - the self-employed.	Energy advice program, energy tax, electricity tax, VAT, ETS	Including information in the heating bill, ex-tending existing advice programmes (including distribution of heat alert devices), smart heat meter rollout

	Type of behaviour	Step 2		Step 3	Step 4			Step 5	Step 6
		Savings		**Ease of imple-men-tation**	**GHG abatement cost (EUR (2010) / t CO_2e)**		**Distributional effects**	**Existing policies**	**Proposed policies**
Measure		**2020**	**2030**		**2020**	**2030**			
Housing									
5: Insulation of heat distribu-tion lines	Investment, efficiency	13.5 TWh/a (48.6 PJ)	5 TWh/a (18 PJ)	2	n.a.	n.a.			
7: Investing in building auto-mation	Investment, efficiency	2.1 TWh/a (7,6 PJ)	4.0 TWh/a (14,4 PJ)	2	-440.5	-602.7			
Appliances									
10: Reduction of multiple ownership (TV and cold ap-pliances)	De-investment, sufficiency	5.4-7.3 TWh/a (19.5-23.4 PJ)	5.36-6.2 TWh/a (19.3-22.3 PJ)	1	-265.5 to -585,4	-437,1 to -1009,4	Relative savings highest for - high income households - bigger households - HH whose head is working or pension-er	Information in-struments, elec-tricity tax, ETS	**Scrap bonus**, free col-lection of old applianc-es, creation of a data-base, life cycle cost indication at point of sale, information cam-paigns, tax disincen-tive
11: Upper limit for individual appliance consumption	Investment, sufficiency	0.18-1.1 TWh/a (0.6-4 PJ)	0.25-1.7 TWh/a (0.9-6.1 PJ)	2	-265.5 to -585,4	-437,1 to -1009,4		EU energy label, EU Ecodesign, Blue Angel (ecolabel), Ener-gy Star	**Feebate system**; up-per consumption limits in Ecodesign and En-ergy Label regulations,
12a: Suffi-ciency-related changes in usage behav-iour (TV and electric laun-dry drying)	Usage, suf-ficiency	7.2 TWh/a (25.9 PJ)	5.6 TWh/a (20.2 PJ)	2	-265.5 to -585,4	-437,1 to -1009,4		Information web-sites, energy ad-vice program, compulsory user information in Ecodesign regu-lations, ETS, electricity tax	Extension of existing advice programs**; cross-cutting: cap and trade system for electricity sales**

Source: Author's own

Contribution to Energy Concept targets

To determine possible contributions of the measures to the targets of the Energy Concept, the percentaged targets have been converted into petajoules and broken down to the household sector (assuming that all sectors would have to contribute equally). Then, a “distance to target” was calculated for the last available year 2012: Savings between 2008 and 2012 were deducted from the goal to determine the “remaining” petajoules that have to be saved until 2020 or 2050 to achieve the target.

Finally, a rough aggregation method was applied to account for the fact that some of the measures overlap and the implementation of one measure would reduce the potentials of others. For example, lowering room temperature would reduce the savings that could be expected from reduced living space, and vice versa. For this purpose, measures were grouped to clusters. For each cluster, the biggest individual measure was considered as the “minimum” potential and the sum of all measures in the cluster as the “maximum” potential. As a more realistic approximation of total cluster savings, the average of the minimum and the maximum was calculated. The results for the need areas of housing and appliances are shown in Table 4, along with an indication for which target of the Energy Concept each cluster would be relevant.

Table 4: Potentials of clusters of measures

		Final Energy Savings 2020 (PJ)			**Final Energy Savings 2030 (PJ)**			**Relevant for target**
Cluster	**Measures**	**Min**	**Max**	**Av.**	**Min**	**Max**	**Av.**	
Housing	1b,2,3,5,7	86.4	164.0	125.2	135.7	256.5	196.1	Primary energy, heat demand buildings, electricity
Appliances	10,11,12a	30.2	60.1	45.2	28.1	54.4	41.2	Primary energy, electricity
Total PJ		**242.6**	**417.8**	**330.2**	**365.8**	**639.9**	**502.8**	

Source: Author’s own

Finally, in order to assess the contribution of the savings potentials shown in Table 4 to the electricity and primary energy related targets, the shares of different fuels in the final energy savings were estimated based on various sources, and conversion factors were applied to convert the respective fuels to primary energy. A lower and upper value is given that is due to different conversion factors. [14]

Fi

gure 1 shows the 2012 distance to the 2020 and 2050 targets and the average projected savings of the applicable measures for each indicator in 2020 and 2030. No savings could be projected for 2050

[14] Details will be available in the project report.

as such long-term forecasts are too speculative, therefore 2050 targets serve illustrative purposes only.

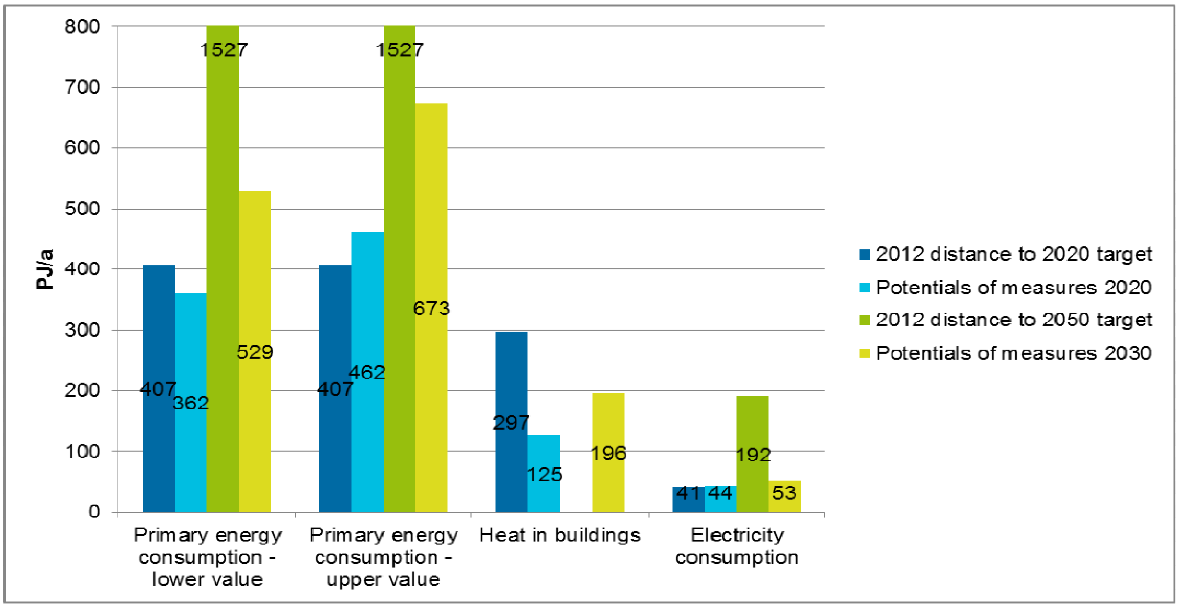

Figure 1: Contribution of selected measures to savings goals of the German Energy Concept

Source: Author's own

In total, the selected measures can make a quite substantial contribution to the targets, broken down for the household sector. In some cases, 2020 targets will even be exceeded. However, this is a theoretical potential and it is not clear what share of it could actually be reaped by deploying policy instruments. The following section illustrates the analytical steps of the project for some appliances-related measures, including the development and assessment of policy instruments.

Example: Measures in the field of electric appliances

Step 1: Selection of measures

In the first screening round, the following measures had been selected as promising:

M8: Highly efficient appliances. This means the replacement of existing appliances by highly efficient ones. It could take the form of "better replacement" (buying a highly efficient appliance instead of an average one, if an appliance is replaced anyway) or "early replacement" (replacing an appliance by a highly efficient one before the end of its lifetime if this is, in a lifecycle view, ecologically favourable[15]).

M9: Low-investment measures. This means for example the replacement of traditional light sources by CFLs and LEDs and the application of switchable connector strips and timers to avoid stand-by.

M10: Reduction of multiple ownership. This means taking secondary appliances permanently out of usage. It does not necessarily mean physically disposing of them.[16]

M11: Upper limit for individual appliance consumption. This means that individual appliances will not consume more than a defined amount of energy (for example in terms of on-mode power or yearly consumption). The measure could be in place for some or all appliances and implemented by state regulation or by consumer action (see below step 2).

[15] The LCA assessment is necessary for compatibility with resource efficiency targets. Research shows that early replacement is environmentally advantageous for example for cold appliances that are older than 10 years [Rüdenauer]

[16] We do not see a conflict with lifetime extension or resource efficiency targets. As it is assumed that no additional appliances are bought instead, there is no additional resource consumption.

M12: Changes in usage behaviour. These changes were split up into efficiency-related changes (12a) and sufficiency-related changes (12b). Efficiency-related changes include various activities such as “efficient cooking” (matching pan and plate size; switching off in time), “efficient washing” (e.g. at full load) and “efficient cooling” (e.g. not placing the cold appliance next to a heat source, regular defrosting). Sufficiency-related changes implied the reduction of activities that consume electricity.

After a preliminary assessment of the savings potentials, M8, M9 and M12a were not followed upon. M8 turned out to be covered by the policy instruments assumed in the EWS (mainly Ecodesign and Energy Label) so that no or little additional savings were expected. The same was true for the lighting part in M9 while the other components of this measure could not be modelled for lack of data on current usage. For the same reason, M12a could not be modelled.

Step 2: Assessment of savings potential

Measures M10, M11 and M12b were assessed. For budget and data availability reasons, each measure was operationalized by way of example. This means that the quantifications described below do not represent the full potential of each measure, but only a relevant share of it with respect to specific appliances. For all three measures, a bottom-up model called DEESY was used that includes stock data, usage times and average electricity consumption for various appliances.

M10: Reduction of multiple ownership

TV sets and cold appliances were chosen as examples here because they represent a relevant share of household energy consumption (cold appliances around 15 %; consumer electronics total 8,4 % according to [19]). Also, there is a clear trend to multiple ownership, and good stock data are available. According to BAU projections in DEESY, ownership will develop as shown in Table 5.

Table 5: BAU ownership of TVs and cold appliances in Germany

Year	2005	2010	2015	2020	2025	2030
TV per household	1,45	1,51	1,52	1,53	1,53	1,53
Cold appliances per household	1,56	1,58	1,62	1,65	1,68	1,72

Source: Author’s own

It was now assumed that ownership in the target years would be 1,3 (or, in a sensitivity variant, 1) per household for TVs and 1 for cold appliances instead. For TV, elasticity of usage was assumed to be 50%, meaning that the reduction of usage time would be half the reduction of appliances (the first appliance would be used longer instead). Results are shown in Table 6.

Table 6: Savings through reduction of multiple appliance ownership in Germany

Measure	Operationalization	Savings 2020	Savings 2030
Reduction of multiple ownership (Cold appliances)	Reduction to 1 appliance per household	4,6 TWh/a (16,6 PJ)	4,7 TWh/a (16,9 PJ)
Reduction of multiple ownership (TV)	Reduction to 1.3 appliances per household, elasticity = 50%	0,8 TWh/a (2,9 PJ)	0,66 TWh/a (2,4 PJ)
	Reduction to 1 appliance per household, elasticity = 50%	1,9 TWh/a (6,8 PJ)	1,5 TWh/a (5,4 PJ)

Source: Author’s own

M11: Upper limit for individual appliance consumption

This measure was modeled for TV sets. First, there is a clear trend to larger screen sizes that in part cancels out efficiency gains. [18]. Secondly, good stock data for TV sets of various sizes were available.[17] DEESY includes four generic size categories of TV sets, called S,M,L, and XL with consumption and projected numbers (in million) as shown in Table 7

Table 7: Energy consumption and stock development of different size TVs in Germany

Year / Type	2010		2015		2020		2025		2030	
	kWh/a	**Mio.**	**kWh/a**	**Mio.**	**kWh/a**	**Mio.**	**kWh/a**	**Mio.**	**kWh/a**	**Mio.**
TV S	153,3	36.04	131,4	27.17	109,5	21.74	95,0	16.58	80,0	11.26
TV M	245,3	19.38	213,2	26.56	181,0	29.62	150,0	32.34	120,0	35.03
TV L	335,8	4.24	299,3	6.79	262,8	10.08	230,0	12.44	200,0	15.01
TV XL	480,3	0.91	427,8	1.24	375,2	1.57	335,0	2.07	300,00	25.02

Source: Author's own

Two variants were calculated: In V1, the average consumption of all XL TV sets in the target years was reduced to the consumption of an L TV set. In V2, the average consumption of all XL and L TV sets in the target years was reduced to the consumption of an M TV set. Stock development was kept constant. Table 8 shows the results.

Table 8: Savings through absolute limits on TV energy consumption in Germany

Year	2020		2030	
BAU consumption (GWh/a)	10.981,95		8.857,36	
Reduced consumption (GWh/a)	**V1**	**V2**	**V1**	**V2**
	10.805,09	9.852,18	8.607,14	7.206,05
Difference	176,86	1.129,77	250,22	1.651,30

Source: Author's own

M12b: Sufficiency-related changes in usage behaviour

Two examples were considered that could be modelled by modifying standard usage times included in DEESY. It was assumed that

- in households with an electric laundry dryer, laundry would be dried on the line during four summer months instead of using the electric laundry dryer (implying that there would be no additional energy consumption for space heating);
- TV watching time would be reduced by 50%.

Appliance stock and characteristics were kept constant. Table 9 shows the results.

Table 9: Savings potential through reduced laundry drying and TV watching, Germany

	Laundry drying		TV watching	
	2020	**2030**	**2020**	**2030**
BAU consumption (GWh/a)	5,191	3,528	10,982	8,857
Reduced consumption (GWh/a)	3,461	2,352	5,491	4,429
Difference (GWh/a)	1,730	1,176	5,491	4,429

Source: Author's own

Step 3: Evaluation from a behavioural science point of view

In this step, information was collected from scientific literature on context and antecedents of investment and usage behaviour in the field of electric appliances, and on factors promoting or inhibiting

[17] Another obvious candidate would be washing machines [28]. However, total savings potential for washing machines is low as compared to other appliance types [20], so they were disregarded here.

energy saving behaviours. Both conceptual models of behaviour and empirical studies were used. Table 10 gives an overview of the results. The table is not exhaustive; it presents the factors that have been established as relevant in the literature reviewed. Gaps do not necessarily mean that other factors are not relevant but can be due to the fact that they have not been studied.

Table 10: Factors influencing appliance-related energy saving (literature review)

Target variable		Energy-saving behaviour in the field of appliances (general)	Total appliance energy consumption	Purchase of highly efficient appliances	Modification of usage behaviour	Multiple ownership
General antecedents	Socio-demographic	Gender	Appartment size, household size, ethnic group, urban setting		Household size and composition	TV: family size, income; cold: flat size
	Context / Environment/ Technology	Social milieu; energy price; behaviour and norms of peer group; difficulty of the respective behaviour	Neighbourhood context	Current electricity use; appliance price; retail strategies; type of appliance (relevance of energy efficiency differs for different appliances)	Socio-technical "co-evolution" (of technology, practices and norms)	
	Psychological	Self-concept; knowledge of environmental impact; interest in energy saving; perception of cost /benefit; attitude, norms, perceived behavioural control, intention, status, emotions; purchase motives (e.g. functionality, design, efficiency)		Knowledge about appliance energy use; motivation to save energy, self-concept, perceived behavioural control		
Conducive factors	Socio-demographic	female gender;		Education; living in a rented apartment		
	Context / Environment/Technology	Timely and tailored feedback on energy use;	Identification of "core" appliances / behaviours with great impact that can be modified	Specific social milieus (e.g. post-materialist, bourgeois middle class); existence of support programmes		
	Psychological				High perceived behavioural control, self-concept as innovative	
Inhibiting factors	Context / Environment/Technology	Option to save cost by changing the supplier; individual potentials are small and do not seem worthwhile;		No control (built-in kitchen in rented flat); "stress purchase" when appliance is broken		
	Psychological	Lack of knowledge about electricity consumption, price, savings options & priorities; overestimation of own knowledge and savings; fear of status loss; family conflicts		Priority of other purchase criteria; first cost bias; lack of information on life cycle cost, energy label or how to identify efficient appliances; for TV: lack of knowledge on energy consumption; lack of trust; lack of capital; high information cost	Habits; energy consumption practices are socially and technologically embedded and "fixed"; loss of comfort	

Source: Author's own

Next, these general results were applied to the specific measures in order to determine how difficult it would be to implement them. The measures were considered in their broader sense described in Step 1, not restricted to the specific examples assessed in Step 2.

M10: Reduction of multiple ownership

The measure itself has not been discussed in the literature. There is one older source in which reasons for multiple ownership are surveyed [21]. Main reasons given by respondents are for cold appliances: need for more storage space, and for TVs: presence of multiple family members. However, the statement about storage space should be treated with caution. Anecdotical evidence e.g. from energy advisors shows that often secondary appliances run empty or with very little content; main reason being that they are kept as a reserve when a new appliance is bought and not taken off-grid.

Taking appliances out of usage is a de-investment and sufficiency decision does not imply monetary cost (except for maybe a small fee if they are physically disposed of). However it can entail important non-monetary cost in terms of comfort, or even family conflicts over usage. These costs will depend on how much the appliance is actually used or needed. We assume that the cost is lower in the case of cold appliances as the necessary storage space will often be available or can be provided by better organization. In contrast, costs for reducing the number of TV sets are assumed to be higher: if family members cannot watch TV in parallel, conflicts may occur. Furthermore, in the case of TVs, monetary benefits will be proportional to non-monetary costs in terms of reduced viewing time. In the case of cold appliances which consume energy even if not used fully, benefits will probably exceed costs.

Policy instruments such as a “scrap bonus” can make the disposal of secondary appliances more attractive. However, they will only be motivating if the household feels that the appliance is actually not needed or used much. A TV set that is not used much, on the other hand, will not consume much energy. Therefore, such a bonus appears more appropriate for cold appliances than for TV sets. Also it is not easy to design such a policy instrument so that it will be effective (see below Step 6). Therefore this measure is considered as difficult to implement and ranked “1”.

M11: Upper limit for individual appliance consumption

There are various ways how this measure can be realized. Policy instruments such as EU Ecodesign could define such an upper limit. Or consumers could decide for limiting appliance energy consumption in their purchase decision, e.g. by choosing a smaller appliance or one with less functionalities. In this step, the focus of the analysis is consumer behaviour.

The measure is not considered in the literature. It can be classified as a sufficiency measure and an investment decision. Therefore, barriers and inductive factors are relevant at the moment of the purchase decision. A relevant barrier is lack of information. For example, consumers often do not know that a bigger appliance may consume more electricity than a smaller one even if it has a better energy class. The current energy label does not highlight absolute energy consumption much, and the calculation formulae favour bigger appliances, e.g. in the case of TV and washing machines. Also, smaller size appliances may not any more be on offer in large numbers and varieties.[18] Finally, costs occur in terms of loss of comfort, functionality, or status. On the positive side, there are not only energy cost savings but, in some cases, also a lower purchase price. Also, some consumers may not actually need all the functionality that is offered. The balance between monetary benefit and non-monetary cost will vary depending on the individual appliance, needs and motivations.

Policy instruments such as awareness raising, better information (e.g. by a revised energy label), incentives for manufacturers or public procurement can support the measure. It is regarded as challenging, but some of the barriers can be effectively removed. It is therefore ranked “2”.

M12b: Sufficiency-related changes in usage behaviour

While changed usage behaviour implies no monetary cost, psychological and social barriers are strong. A typical barrier is that usage behaviour is part of highly routinized everyday practices which

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[18] This can be established in the case of washing machines, where 4 and 5 kg machines are virtually not on offer any more. For TVs and cold appliances, a market research would be needed to confirm the statement.

are not consciously reflected. Changes imply disruptions of established procedures. Furthermore, it is strongly influenced by social norms of what is normal and desirable (e.g. in terms of hygiene, comfort, safety, or good housekeeping practice). In addition, sufficiency-related behaviour may imply losses of comfort or additional effort. On the other hand, behavioural changes can also imply, besides monetary savings, non-monetary benefits such as satisfaction, pride, sense of control, or the discovery of other / new non-energy consuming pastimes. The individual balance of benefits and costs depends on the behaviour and person(s) in question. Although the barriers are high, we assume that some of them can be alleviated by appropriate education, advice and incentives, and rank the measure with "2".

Step 4: Economic evaluation

GHG abatement cost

The goal of this step was to determine the specific greenhouse gas abatement costs for each measure. The measures were defined by way of example as in Step 2 above. GHG abatement costs are costs needed to avoid an additional unit of GHG emissions as compared to a reference situation (in this case, the EWS). Negative abatement costs indicate a monetary gain.

Normally, GHG abatement costs include both investment costs of the measure and changes in running cost. The measures considered here do not imply investment costs so that only the generated energy savings are figured in, resulting in negative abatement costs.[19]

For all appliance-related measures considered here, the fuel is electricity. Therefore, the relevant data are electricity cost on the one hand and the emission factor for electricity generation on the other (because the latter determines the GHG saved per unit of electricity saved). The emission factor depends on the fuel mix used for generating electricity. Two variants were calculated: one with an average fuel mix, and a sensitivity variant where it is assumed that the fuel mix of the saved electricity is that of the marginal power plant(s). Marginal power plants are those that would be switched off first in case of savings because they have the highest running cost. These would usually be gas-fired plants. The following values were used:

Table 11: Input parameters for calculation of GHG abatement costs

	2020	**2030**
Electricity price (EUR (2010) / GJ)	78,71	92,53
Emission factor (basis) (g CO_2 / kWh)	1067	762
Emission factor (sensitivity) (g CO_2 / kWh)	484	330

Source: Author's own

[19] For the measure "upper limit of energy consumption" there might even be negative investment cost because smaller appliances are cheaper. However, as this is difficult to quantify, investment costs are not figured in in this analysis.

Table 12 shows the results. For an explanation of the constant abatement costs across measures for each variant and year see p.7.

Table 12: Net cost and GHG abatement cost for appliance-related measures

		2020			2030		
		Net cost (Mio. EUR (2010)	**Avoided GHG (Mt CO_2e)**	**Abate-bate-ment cost**	**Net cost (Mio. EUR (2010)**	**Avoided GHG (Mt CO_2e)**	**Abate-ment cost**
M10: Reduction of multiple own-ership (V1)	Basis	-1537,2	5,8	-265,6	-1782,1	4,1	-437,1
	Sensi-tivity	-1537,2	2,6	-585,4	-1782,1	1,8	-1009,4
M10: Reduction of multiple own-ership (V2)	Basis	-1841,8	6,9	-265,6	-2065,2	4,7	-437,1
	Sensi-tivity	-1841,8	3,1	-585,4	-2065,2	2,0	-1009,4
M11: Upper lim-it consumption, V2	Basis	-311,7	1,2	-265,6	-566,3	1,3	-437,1
	Sensi-tivity	-311,7	0,5	-585,4	-566,3	0,6	-1009,4
M12b: Usage behaviour	Basis	-2040,2	7,7	-265,6	-1865,4	4,3	-437,1
	Sensi-tivity	-2040,2	3,5	-585,4	-1865,4	1,8	-1009,4

Source: Author's own

Distributional effects

A distributional analysis has been conducted for M10, Reduction of multiple ownership, V2. The analysis is based on the "Einkommens- und Verbrauchsstichprobe" (EVS; "Income and Consumption Sample"), a representative survey on the income and spendings of German households that is conducted every 5 years. The survey shows that multiple appliances are more common in households with higher income and in bigger households. Consequently, average electricity savings potentials are higher in these households, too, just because a bigger proportion of these households can be expected to implement the measure. In monetary terms however, savings translate into a higher share of the income in lower-income households. Table 13 shows the results for 2020 (2030 savings are slightly lower).

Table 13: Distributional effects of the measure "Reduction of multiple appliance ownership"

Income decile (weighted net household in-come)[20]	**Low est 5%**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**Av.**
Ø weighted net household income (EUR/month)	706	836	1229	1483	1708	1939	2178	2466	2855	3486	5544	2318
Electricity savings 2020 (% of total el. consumption)	2,3	2,5	3,7	4,2	4,6	4,9	4,9	5,2	5,6	5,7	5,7	4,8
Cost savings 2020 (% of household in-come)	0,15	0,13	0,15	0,14	0,14	0,13	0,13	0,12	0,12	0,1	0,07	0,11

Source: Author's own

The analysis therefore shows that there are no negative distributional impacts.

[20] Income has been weighted with a factor that represents household composition and size.

Step 5: Evaluation of existing policy instruments

In this step, a literature review was conducted to identify all policy instruments that might directly or indirectly (even unintendedly) affect measures in the field of appliance-related energy savings. The current instrumentation has been analyzed, among other things, with respect to governance mechanisms, governance actors and level as well as main target groups in order to determine whether there are any gaps. Furthermore, the effectiveness of a subset of instruments, namely the economic instruments that increase the electricity price, has been assessed in-depth using a literature review and the "intervention logic approach" [17], including an analysis of whether main barriers identified in Step 2 have been addressed.

Table 14 gives an overview of the instruments in place.

Table 14: Political Instrumentation of appliance-related energy saving measures in Germany

Instrument	**Measure addressed**	**Governance mechanism**	**Governance actor**	**Governance level**	**Main target group**		
					Consumers	**Industry**	**Intermediates**
Energy Label	M11	Information	State	EU	1	0	0
Blue Angel label for TV (with upper limit)	M11	Information	State / industry	National	1	1	0
US Energy Star for TV (with	M11	Information	Private	National	1	1	0
Consumer information on the internet	M10, M11 M12b	Information	State / private	Various	1	0	1
Energy advice programme	M10, M11 M12b	Information / incentive[21]	State / private / NGOs	Various	1	0	0
Electricity tax	M10, M11 M12b	Incentive	State	National	1	0	0
Emissions Trading	M10, M11 M12b[22]	Incentive	State	EU	0	1	0
Renewable Energy Law	M10, M11 M12b[22]	Incentive	State	National	0	1	0

Source: Author's own

The analysis shows that the instrumentation is generally rather weak with respect to the measures in question. Its core pillars are information and incentives. Information measures can in fact alleviate some of the identified barriers relating to lack of information. But they are currently not implemented systematically and large-scale. Also, information on its own will not counteract the trend to bigger appliances that is driven by the desire for comfort and functionality. Incentives provided via the electricity price are not intended by the instruments and come rather as a side effect, and they are not very effective either. First, the price signal is rather general and does not suggest specific savings measures. Secondly, electricity consumption has proven to be rather price inelastic, meaning that only more drastic increases have an effect. Finally, consumers in a liberalized energy market can generally save cost easier and more effectively by changing their supplier than by saving energy.

M11, upper limit for individual appliances, is supported directly by some of the current instruments, but only weakly. Some informational instruments include such limits. For example, there is an upper limit in the current German Ecolabel, Blue Angel, but the label has very low market penetration. Also, progressive efficiency standards (meaning higher efficiency requirements for larger appliances) are im-

[21] Some include free giveaways such as LEDs or connector strips.

[22] Insofar as it makes electricity more expensive.

plemented in the Energy Star and will be included in the current revision of the EU Energy Label for TVs. This is a step in the right direction to correct misleading information, but not sufficient on its own to spur large-scale behaviour change.

Step 6: Proposed new policy instruments

In this step, new policy instruments proposed by different actors were screened, using the same structure as in Step 5. For selected instruments, an ex-ante evaluation was conducted, assessing effectiveness, consistency with other policy goals, social impact and legal aspects. W here possible, a quantification of possible impacts on GHG and energy savings has been done.

In the field of appliances, the following instruments were assessed: a “cap” on the amount of electricity that can be sold by each supplier; a “Feebate” system that would give a rebate on highly efficient appliances while charging inefficient appliances with a fee; an obligation to inform about life cycle costs at the point of sale, and a “scrap bonus” for the disposal of old appliances. In the following, a very short summary of the results is given of the electricity sales cap, the life cycle cost display and the scrap bonus, because these instruments directly address the measures discussed here (while the Feebate system focuses on highly efficient appliances).

Electricity sales cap

The cap has been proposed by the German Expert Council on Environmental Issues (SRU) [22]. It is a cross-cutting instrument that sets an upper limit for the electricity sales of each supplier. The cap can decrease over time. The “electricity selling rights” are tradable. It is assumed that the instrument provides an incentive for suppliers to promote energy savings in households because otherwise they would have to buy certificates.

The instrument allows for a precise steering of emissions. Whether it addresses the specific barriers for households that have been described in Step 2 (information deficit, lack of incentives, fear of loss of status or comfort) depends on the concrete activities that would be implemented by suppliers. Its quantitative effects depend on the level of the cap. If, for example, the amount of sold electricity is reduced by 1% per year, savings of 36 TWH in 2020 and 91 TWh in 2030 can be expected.

The instrument is expected to have positive distributional effects. As low-income households generally consume less energy, it is expected that suppliers compete for these households and try to attract them e.g. by offering a progressive tariff structure with low prices if consumption is low. Also, the lawfulness of such an instrument has been confirmed in a recent study [23].

Because of its potential to steer electricity consumption in a targeted and effective way while potentially having positive distributional effects, the study recommends this instrument. To be effective, it should however be combined with specific instruments (e.g. information, advice, incentives, regulatory instruments) that facilitate specific measures which can be used to achieve the savings targets. While those specific instruments will be in part developed by suppliers, a conducive national or European framework is helpful (e.g. large-scale, targeted and quality-assured energy advice, revised energy labels, incentives or regulations that support energy-saving features in appliances).

Life cycle cost information

The instruments means that retailers will be obliged to display total life cycle costs (LCC) of appliances (purchase cost and expected running cost) at the point of sale, in online marketing, and possibly in advertising. This can be done in the form of yearly costs, or costs over the whole (standardized) product lifetime. The costs are calculated according to a standardized procedure. The instrument has been recommended by various recent studies (e.g. [24]) and tested in trials in the UK [25], Germany [26], and other European countries [27].The display of the “true” overall cost could counteract the “first cost bias” by demonstrating that an efficient appliance can be economically attractive even if it is more expensive at first sight. It could also give an additional boost for appliances with lower absolute energy consumption if their cost advantage over the whole life cycle is transparent.

In spite of the theoretical advantages, the instrument faces difficulties in practice. First, there are methodological difficulties in determining the LCC, related to uncertainties in energy price, usage patterns, or product lifetime. Secondly, experience from the trials shows that the information had little effect. The highest savings were achieved in the UK trial for washer-dryers with on average 6.64 kWh per sold appliance and year. The information was either not recognized by the clients or did not influence the purchase decision much. There are several possible reasons: clients are unfamiliar with the concept, they do not trust the information, potential cost savings are too low, or efficient appliances do not really have a cost advantage because of the high purchase price. The effectiveness will however probably depend on the concrete design of the instrument, e.g. the design of the label, accompagnying information, the choice of appliance type, and the decision to display yearly or total cost.

The instrument itself supports cost savings and does therefore not have negative distributional effects. However, low-income households might have difficulties in financing an appliance with high purchase cost even if the life cycle cost is favourable. Additional instruments, such as micro credits, can help here.

A legal question is whether EU Member States are authorized to introduce national energy-related labels beside the EU Energy Label. However, as information on monetary cost is so far not regulated on EU level, and would also not make much sense because of the starkly differing energy prices between member states, a national label obligation to display LCC seems compatible with EU law.

While the instrument does currently not seem very effective in terms of energy savings, the study still sees it as worthwhile to implement it if only to correct information asymmetries and increase transparency for consumers. If quality-assured by an independent authority and accompanied by extensive public relation measures, and if picked up by manufacturers as a marketing tool, the “second price tag” can gradually become better known and more effective.

Scrap bonus

The idea of a scrap bonus is to provide a financial incentive for the disposal of old, energy-consuming appliances. Eligibility criteria can be linked to efficiency (e.g. appliances below class B) or absolute energy consumption (e.g. cold appliances above 400 kWh/year).

The instrument addresses barriers such as lack of awareness and incentives. In order to motivate households to dispose of appliances, procedures must be simple and the incentive sufficiently high. It does not seem possible to guarantee that secondary appliances are completely taken out of usage. Households may instead use the bonus to purchase a new, more efficient secondary appliance. This usage weakens the overall savings effect of the instrument, but still generates some positive effect. Furthermore, the instrument may produce rebound effects, when the bonus is used to finance other energy-consuming goods or services, and it can have important free rider effects.

A quantification of savings induced by a scrap bonus is not performed in the study as it depends very much on highly variable and speculative assumptions.

The instrument could have some problematic distributional effects. As multiple appliance ownership is more frequent in higher income households, it amounts to a subsidy for wealthier households.

From a legal perspective it must be ensured that the funds are spent economically and efficiently.

All in all, the study does not recommend the instrument due to its low accuracy and high risk of free rider and rebound effects.

Conclusions and outlook

The range of human behaviour is broad. Investment in efficient appliances features high in energy and climate scenarios, and some types of (efficient) usage behaviour are targeted at least by information campaigns even if results are limited. But other types of behaviour have been largely overlooked so far – be it because of their bad image or because they do not seem to be addressable by policy instruments, or both. Some of them do have a large energy savings potential, though. This is true for lifestyle changes and for certain “sufficiency” or “curtailment” behaviours – notably for those that resemble, in their structure, to an investment decision: after a one-time effort, energy savings come automatically. Examples in the field of appliances are the purchase of appliances with low absolute energy consumption, or the reduction of the number of appliances in the household. Even more effective are measures in the housing or mobility sector that have not been discussed in this paper but are presented in detail in the study – such as the reduction of per capita living space, the disposal of the private automobile or the purchase of a smaller one.

It does not seem self-evident that such behaviours could or should be promoted by policy instruments. The ideas of individual freedom, of non-interference with the chosen lifestyle or of consumer sovereignty stand in the way, as do possible legal obstacles or (often rightful) doubts that policy could even be effective. In fact, the analysis of measures in the field of appliances shows that although the potentials of sufficiency measures are considerable, they are not easy to reap by way of policy instruments.

The project has shown some ways though in which policy can creatively approach and tap these potentials – even more so in the areas of mobility and housing than in the area of appliances. If total energy consumption shall really go down, policymakers are just one actor and policies just one component in a larger social transformation that includes changes in technology, norms, markets, and social practices as well. But they are an important actor who can, by setting a framework, trigger further action by others. A comprehensive look from different disciplines as applied in this project will help to identify the most promising avenues and encourage an energy policy that actively and creatively engages with all relevant varieties of human behaviour.

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Consumer importance on sustainable laundry care. Results of an online-survey in Germany.

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Abstract

Laundry care is a frequent activity in the household and its resource consumption is remarkably high. In this paper, the impact of consumer behaviour on the sustainability of laundry care is analysed. First insights into a study of consumer behaviour in Germany are presented. Data from 1120 participants were collected in an online-based survey in 2014. The questions focused on textiles, sustainability and pre-washing tasks, such as sorting of laundry and the composition of laundry loads as well as in the choice of washing programmes and the dosing of detergents. The main objective of the presented survey was to gain information for a better understanding of consumer behaviour and consumer handling of laundry items. Results concerning pre-washing tasks like sorting and preparing the laundry as well as consumer attitude towards sustainability are presented in this paper.

Introduction

Laundry care is a frequent activity in the household and its resource consumption is remarkably high. In Germany, private laundry care consumes 5.5 billion kWh of electricity, 380 million cubic metres of drinking water and 600.000 tons of detergent each year. [1] Four (4) kg of laundry is washed per week and person in Germany; in total an amount of 20 billion tons of textiles each year. [2]

A systematic approach of the laundry care and its functions and parameters must be the basis for research concerning analysis of consumer behaviour and improvements in sustainable laundry care. Laundry care can be described as a technical system with the following three subsystems: pre-washing, washing and post-washing. Main input parameters are dirty laundry, detergent, water and energy, whereas the main output parameters are clean laundry, dirty water and heat energy. The washing itself is mainly performed automatically by the washing machine, whereas the pre- and post-washing tasks such as collecting and sorting as well as ironing and folding of the laundry are performed by the consumer. [3]

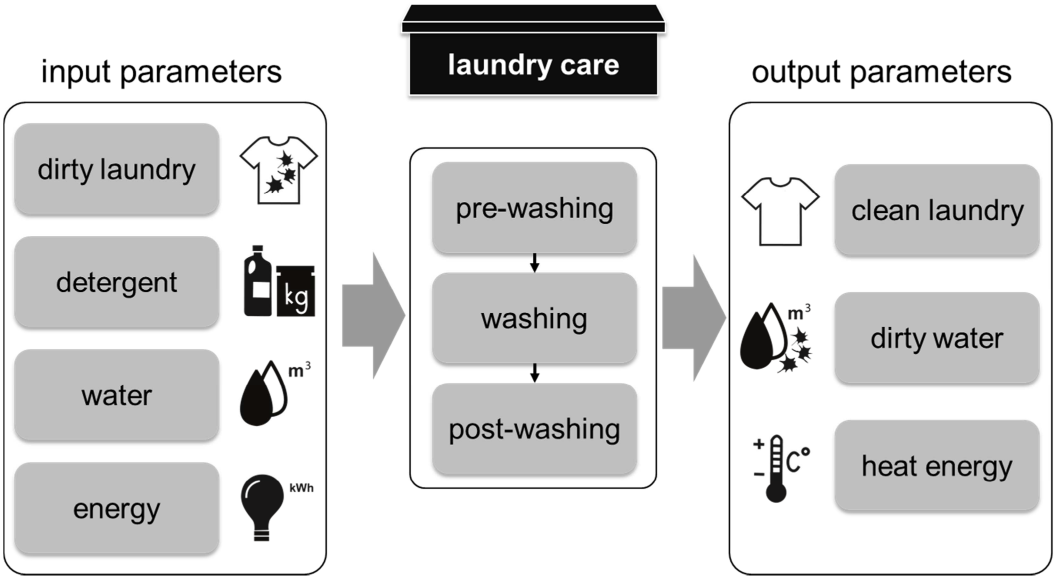

Figure 1: Laundry care technical system

Sustainable laundry care includes the reduction of resource consumption (energy and water) during the washing process as well as maximally gentle laundry care. Gentle care of textiles reduces mechanical, thermal and chemical stress and extends the textile product life cycle. Improvements in optimising the sustainability in laundry care have to focus on an understanding of 1) the technical washing process in the washing machine and 2) consumer behaviour. Those are the main objectives of the research project *Household Appliances for Laundry Care,* in which experts from three universities and one industrial partner work in an interdisciplinary team to optimise resource efficiency. Fields addressed by team members include clothing technology/fabric processing, fluid system dynamics and mechanical engineering.

This paper focuses on textiles and consumer behaviour in the pre-washing subsystem. The gentle care of textiles always depends on the textile properties. Each single textile product has its own special properties that result from *e.g.* fibre properties, fibre composition, mass, thickness, tensile strength, friction or water absorption capacity. The properties result from the construction of the fabric (woven or knitted fabric), the construction of the yarns (twisted yarn or filaments) and the construction and composition of the fibres (natural or man-made fibres) as well as from the treatment in the finishing sector. Other properties such as size of the laundry item or additions like laces, zippers or decoration also influence the textile care requirements.

Depending on the textile properties, dirty laundry that has to be washed is sorted and composed into laundry loads and a matching washing programme, washing temperature and detergent must be chosen by the consumer. Therefore, every textile product is tagged with information concerning fibre composition and care instructions by the manufacturers. In Germany the fibre declaration is mandatory, whereas inclusion of care instructions is voluntary. The fibre declaration is mandated by EU Regulation No 1007/2011 on textile fibre names and related labelling and marking of the fibre composition of textile products. [4] The care instructions consist of different pictograms concerning five care-related topics, specifically washing, bleaching, drying, ironing and professional textile care. In most countries the pictograms are registered trademarks and property of GINETEX, the international association for textile care labelling. [5] The care label also contains additional information, *e.g.* “use mild detergent”, “wash inside out” or “wash separately”. All the information given on the care label and the information concerning fibre composition help the consumer to sort laundry, decide the composition of laundry loads and choose the best washing programme, washing temperature and detergent to achieve the best washing result with gentle laundry care.

This paper focuses on the pre-washing subsystem. The impact of consumer behaviour on sustainability and successful laundry care is extremely high in this phase. Depending on laundry sorting and preparation, on the choice of a washing programme and temperature as well as on the choice and dosing of detergent the resource consumption, stain removal and gentleness of care vary. In this paper, results concerning consumer attitude towards sustainability, existence of different types of laundry in the households and consumer handling of laundry items such as the sorting and preparation of laundry items for washing (pre-washing tasks) are presented. Further more insights into results concerning criteria for detergent choosing and dosing, washing programmes, washing temperatures and additional functions are given.

Objective and Methodology

The main objective of this paper is to analyse if consumer handling of textiles in the pre-washing phase can be improved to achieve a better and more sustainable result of the washing process. The main focus is on an improvement of a gentle laundry care. Deficits in consumer behaviour will be detected and recommendations for improving sustainable laundry care will be formulated.

Data from a study of consumer behaviour is used. The main objective of the study is an analysis of consumer behaviour within the three subsystems of the technical system laundry care with a special focus on textiles. An online survey was developed and implemented in spring and summer of 2014. The evaluation of the online survey began in autumn of 2014. In the online survey, data from 1120 respondents were collected. The online survey was developed by using professional software and a link to the survey was sent via e-mail to colleagues, friends and family of the research team and spread via social media and mailing lists. Furthermore invitation flyers were printed and handed out at university events.

The questionnaire consisted of 50 different, mainly closed questions that belonged to the following different themes: social demography, types of textiles in the household, pre-washing-, washing-, and post-washing tasks, detergents, washing machine and sustainability. Depending on the answers given, the respondents were asked different additional questions. For example, if they turn laundry items inside out before washing, they were asked in an additional question which laundry items are turned inside out.

Results

In this chapter the following results from the online survey are presented: consumer attitude towards sustainability, presence of laundry items and pre-washing tasks.

Attitude towards sustainability

Sustainable laundry care includes low energy, water and detergent consumption as well as maximally gentle laundry care. The survey sample was asked how important specific criteria are during laundry care. The respondents were asked to evaluate the importance of the following six criteria: low water consumption, low energy consumption, low detergent consumption, low costs, maximally gentle laundry care and express wash programmes. The low cost criterion does not have an influence on sustainability. The other criteria influence sustainable laundry care – some positively, such as low water consumption, low energy consumption, low detergent consumption and maximally gentle laundry care, some negatively, such as express wash programmes. Express wash programmes use much more energy than normal or ecological washing programmes. They are convenient for the consumer, but influence sustainability negatively.

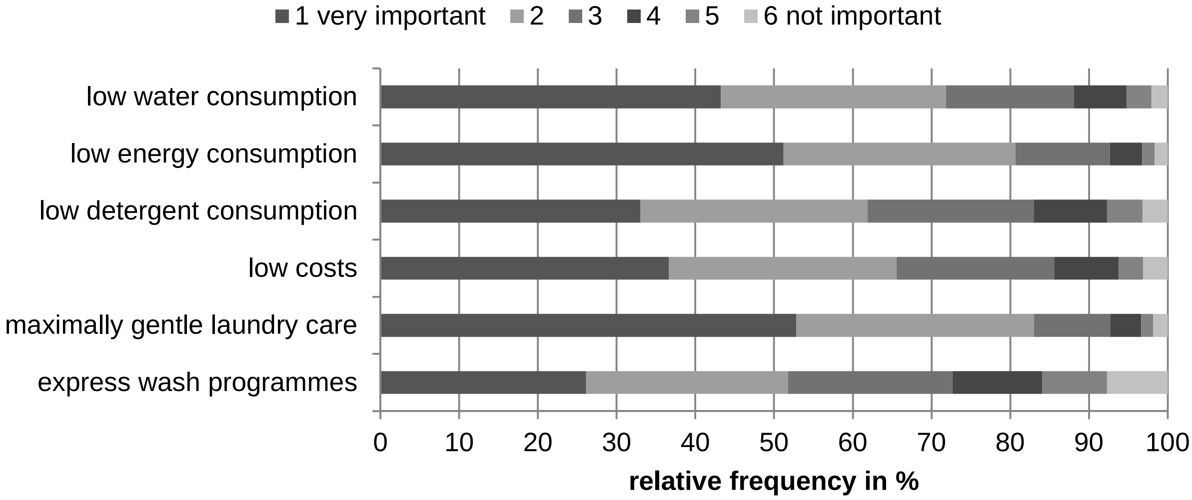

Figure 2: Results from the online-survey concerning consumer attitude towards sustainability (average sample size: 1063 respondents)

Figure 2 shows the results concerning the importance of specific criteria during laundry care. The most important criterion is maximally gentle laundry care, closely followed by low energy and water consumption. Nevertheless express wash programmes are very important for one fourth of the respondents. It can be assumed that some consumers think that express programmes have no big relevance for sustainability.

Existence of laundry items

In total 24 textile products were defined by the research team. The definition mainly focused on the objective that an average consumer should be able to understand the products without needing to be an expert in the textile sciences. Respondents were asked which textile products are present in their households and are washed in the washing machine. The following 24 products were defined: terry towels, dish towels, cleaning towel, bed linen, underwear, bras, socks, tights, trousers, jeans, T-shirts/long-sleeve shirts, cardigans, sweater, shirts/blouses, skirts, dresses, nightwear, printed textiles, decorated textiles, textiles made of wool, textiles made of silk, sportswear, children’s wear and baby clothing.

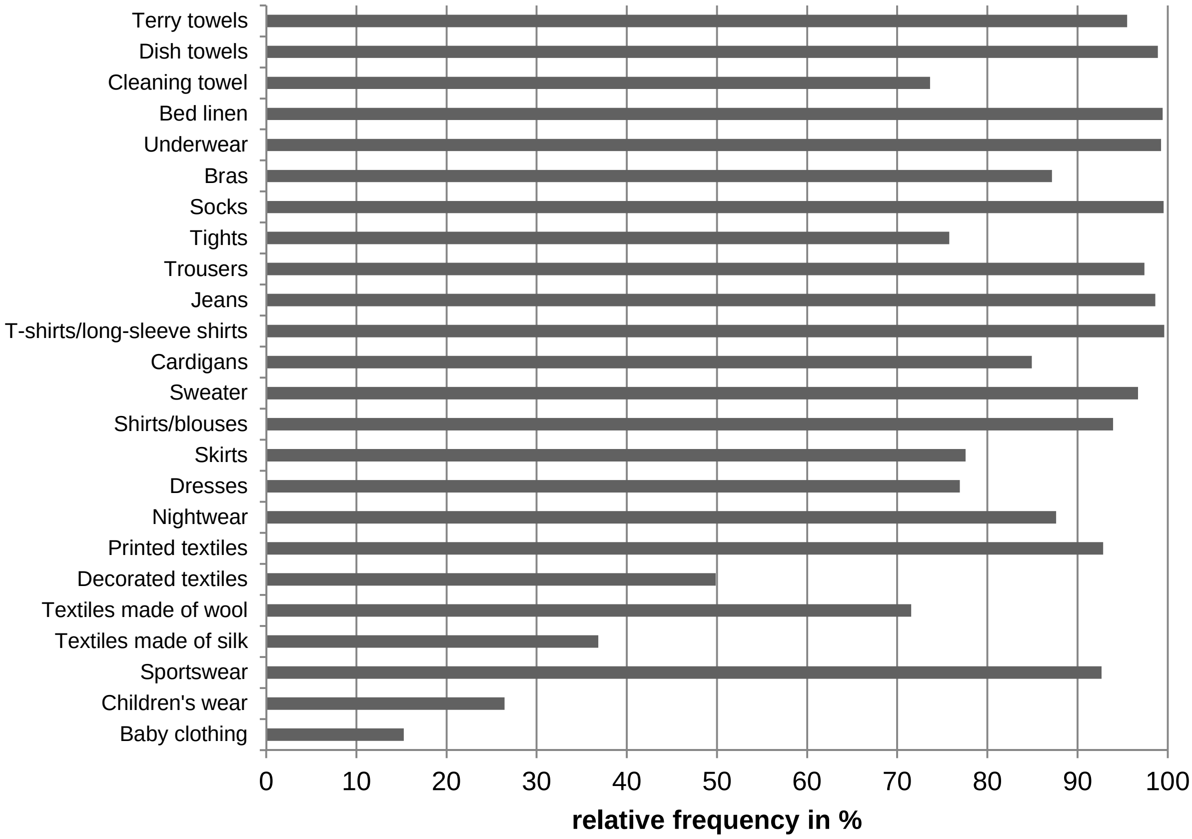

Figure 3: Results from the online-survey concerning the presence of laundry items in the households of the sample (sample size: 1089 respondents)

Figure 3 shows the relative frequency in percent of different laundry items that are washed in the washing machine in the households of the survey sample. Terry towels, dish towels, bed linen, underwear, bras, socks, trousers, jeans, T-shirts/long-sleeve shirts, cardigans, sweater, shirts/blouses, nightwear, printed textiles and sportswear are laundry items that occur in more than 85 % of the households. Cleaning towels, tights, skirts, dresses and textiles made of wool exist in around 70 % to 75 % of the households. Decorated textiles, textiles made of silk, children's wear and baby clothing only exist in less than 50 % of the households.

Pre-washing tasks

Consumer have to undertake several pre-washing tasks before the automated washing process in the washing machine can start. These include the sorting and preparation of laundry items, the choice and dosing of the detergent as well as the choice of a washing programme, washing temperature and additional functions. The survey sample was asked very detailed questions concerning pre-washing tasks. The most relevant results are presented in the following paragraphs.

Sorting of laundry

Is laundry sorted and which criteria are considered? The respondents were asked if they sort their laundry before washing. Those who sort were asked which sorting criteria are more or less important. Possible sorting criteria were given in the answer and respondents could rate the following: textile material, colour, care instructions, type of stain, stain intensity, corresponding detergent, corresponding washing programme, washing temperature and the type of laundry item. In practice, all the given criteria should be considered when sorting the laundry.

In total, 95 % of the survey sample sort and 5 % do not sort their laundry before washing. All of the possible sorting criteria are used by the respondents. The frequency of the used criteria varies. The most important sorting criteria that are considered by about 70 % as important criteria are colour and washing temperature, followed by a corresponding washing programme and the type of textile that is considered between 40 % and 50 % of the respondents. Only about 30 % always pay attention to the textile material and the care instructions on the care label. The least important sorting criteria are the type of stain and stain intensity - only 20 % pay attention to these criteria.

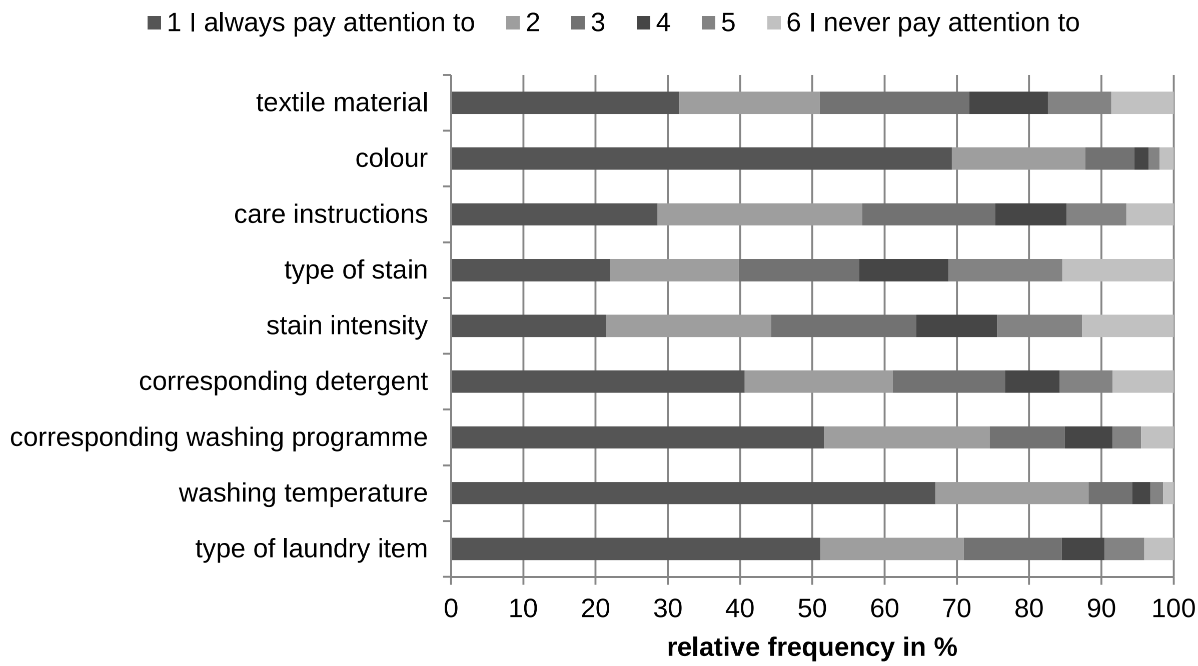

Figure 4: Results from the online-survey concerning sorting of the laundry and sorting criteria (average sample size concerning sorting criteria: 1014 respondents)

Preparation of laundry

The properties of textiles can be affected negatively by mechanical, thermal or chemical stress during laundry care. Examples include a change on the textile surface because of friction, shrinkage or loss of colour of a whole laundry item or the colour of a print. One possibility to reduce the negative effect is turning laundry items inside out before the washing process to avoid damage to the fabric surface or its colour.
The survey sample was asked if laundry items are turned inside out. In total, more than 80 % turn laundry items inside out. In addition, those respondents who turn laundry items inside out before washing were asked which laundry items are turned inside out. Almost three-fourths of the survey sample turn jeans and printed textiles inside out. More than 50 % turn trousers and around 35 % T-shirts/long-sleeve shirts, decorated textiles, bed linen and sweaters inside out.

To avoid damage to the textiles or the washing machine, the laundry items that have special trims, like rivets or bras can be put in meshed washing bags. The survey sample was asked if laundry items are put into meshed washing bags before washing. In total, more than two-thirds use meshed washing bags. In addition, those respondents who use meshed washing bags were asked which laundry items are put into meshed washing bags.

Almost 90 % of the survey sample put bras into meshed washing bags before washing. Some other textiles, underwear, decorated textiles and tights are put into meshed washing bags by 15 % to 35 % of the respondents.

Detergents

Which criteria do consumer take into consideration when choosing and dosing detergents? The respondents were asked this question and could choose between the following criteria: dosing guide, quantity of textiles, type of stain, stain intensity, care instructions, textile material (e.g. cotton, polyester), the degree of water hardness and colour of the textiles.

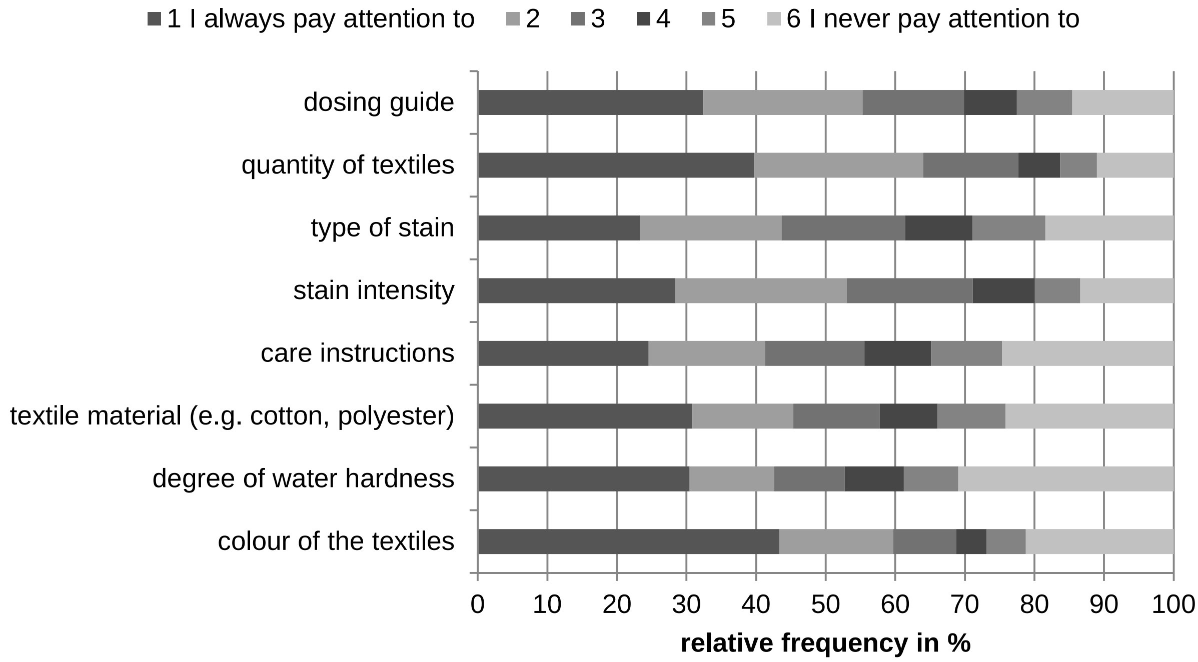

Figure 5: Results from the online-survey concerning detergent choosing and dosing criteria (average sample size concerning sorting criteria: 1017 respondents)

The most common criterion for choosing and dosing detergent is the colour of the textiles, followed by the quantity of textiles and the dosing guide. The care instructions, textile material and the degree of water hardness are the least popular criteria. More than 30 % never pay attention to the degree of water hardness and between 20 % and 25 % never pay attention to care instructions, textile material and colour of the textiles when choosing and dosing detergent.

Washing programmes, washing temperatures and additional functions

As already mentioned the survey focused on consumer handling of textiles. The respondents were asked to sort their laundry virtually and to compose the laundry items into different laundry loads. The differences between the laundry loads will not be considered in this paper. The respondents were also asked with which washing programme, washing temperature, additional functions and how often the specific laundry loads are washed. These data are related to 3577 different virtual laundry loads in total and the most relevant results will be presented in the following paragraphs. The respondents could choose between the following programmes: cotton, easy care, delicates, wool and other. The temperatures were: cold, 20°C, 30°C, 40°C, 50°C, 60°C, 70°C, 80°C and 90°C. Possible additional functions to choose are the following: none, express wash, save energy, anti-crease, pre-wash, extra rinse and other.

The most popular washing programme amongst the respondents is the cotton programme with a temperature of 60°C followed by cotton 40°C, easy care 40°C, easy care 30°C, delicates 30°C and cotton 30°C. However, it should be noted that in total the most popular washing temperature of all programmes is 30°C, closely followed by 40°C and 60°C. Half of the laundry loads are washed with no additional function. The most popular additional functions that are used by the respondents are express washing and energy saving.

Interim conclusion

The results from the online survey show that consumer are very interested in sustainable laundry care. The most important criteria for consumer are maximally gentle laundry care as well as low energy and water consumption during the washing process in the washing machine. The results also show deficits in consumer behaviour, however: 1) not all relevant sorting criteria are considered by the consumer, 2) the laundry items are not prepared the best way for achieving maximally gentle laundry care, 3) the temperature of the most popular washing programme is 60°C, 4) the additional express wash function is used as often as energy saving functions and 5) not all relevant criteria for choosing and dosing of detergent are used.

Discussion

The survey sample was selected trough self-selection of the respondents on the Internet. The population of the survey cannot be defined because there are no data available concerning washing households or Internet users in Germany. Therefore the results of the online survey are necessarily restricted in their representation. Nevertheless the results offer interesting insights into consumer behaviour, especially consumer handling of textiles in the laundry care. With this data the research team will be able to improve research into understanding the technical washing process.

The respondents were asked specific questions concerning the composition of laundry loads, but these results have not yet been evaluated. The evaluated results from the online survey provide data concerning sorting criteria of laundry items as well as criteria concerning choosing and dosing of detergent. There are no data available concerning the criteria of choosing a washing programme and washing temperature, however. Respondents were not asked why they perform their pre-washing tasks the way they do. More questions concerning the choice of the specific washing programme and temperature as well as questions to evaluate the quantity of a composed laundry load could have been asked.

Conclusion

The laundry care technical system and the results of the survey clearly show the role of consumer behaviour in sustainable laundry care. Criteria such as maximally gentle laundry care as well as low energy and water consumption are very important for the respondents.

Depending on the textile material, construction and the treatment in dyeing and finishing, the textile properties and the textile care requirements vary. Only a third of respondents consider the textile material or the care instructions on the care label when sorting the laundry items. Not all respondents prepare the textiles properly before washing. These results show that consumer could know more about the importance of the care instructions and that they should take the care instructions and the textile material into consideration when sorting the laundry to get better gentle laundry care. Experts should rethink and improve the information on the care label to improve consumer awareness and acceptance of care instructions.

The most popular washing programme is cotton 60°C and the additional express wash function is often used by the consumer. The higher the temperature of a washing programme the more energy used. Express washing programmes consume the most energy of all. These results show that consumer need to know more about the correlation between washing temperature and energy consumption as well as the functionality of short programmes to wash more sustainably and save energy and water. Manufacturers, scientists and trade initiatives need to improve communication with consumer on their role in sustainable laundry care.

Depending on the fibre composition in the textiles and the textile colour a matching detergent has to be chosen. Textile fibres can be irreversibly damaged when washed with the wrong detergent, by the wrong washing programme and at the wrong washing temperature. Furthermore, dosing detergent is highly influenced by the degree of water hardness, but also by the size of the laundry load and the stain intensity. More than 30 % do not take the degree of water hardness into consideration when dosing the detergent and for around a fourth of the respondents the textile material and the care instructions are not important when choosing and dosing detergent. The results show that consumer knowledge with respect to selection and dosing of detergent could be improved in the future.

The systematic approach that was offered by the laundry care technical system and the results of the online-survey presented in this paper clearly show the necessity for improvement of consumer behaviour in sustainable laundry care.

Further research needs to focus on an analysis of the relevance of textiles concerning the output parameters such as resource consumption, mechanical action and stain removal. With the results of this survey further research can be done within the research project *Household Appliances for Laundry Care* to optimise resource efficiency in private laundry care.

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Energy consumption pattern of low income households in Thailand

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Abstract

The growth of household income and energy consumption in Thailand has raised the necessity of improving energy efficiency (EE) in the residential sector. This study aims to examine the characteristics and consumption behaviors of low-income households who are expected to become an emerging middle class consuming a large share of national energy demand in the near future. These households are defined to (1) have monthly income between 3,000-15,000 baht (around US$ 100-500), and (2) have access to electricity. The study uses primary socio-economic data obtained from face-to-face surveys of 297 households in Bangkok and four rural areas in Thailand. The survey suggests that the policy implementation could focus on primary education, which is the main education level among this target group, and on female household members who are more likely to be decision makers regarding energy. There are many distinct differences between the households in Bangkok and the rural areas, such as, energy consumption per household, percentage of households using cooking fuels regularly, and rate of owning cooking appliances. Overlooking these dissimilarities could lead to ineffective policy implementation and underinvestment in EE. Furthermore, fluorescent lamps constitute the dominant lighting technology in both urban and rural areas, while there is a potential to encourage the uses of compact fluorescent lamps (CFL) and Light emitting diode (LED) lamps. Although the result shows moderate awareness of EE and knowledge of Thailand's EE Label (also called 'Label No.5'), energy efficient appliances are not widely adopted among this target group.

Introduction

The growth of household income and energy consumption in Thailand has raised the need for energy efficiency (EE) in the residential sector. In 2030, Thailand could have its significant economic mass larger than France today [1]. It is essential to learn the lifestyle and behavior of low-income households, which are on the verge of becoming middle class because they are likely to own more household appliances, consume more energy, and so put more stress on national energy security and the environment in the near future. Therefore, policy makers should be proactive on this particular target group, and should design policy interventions to address this forthcoming demand before becoming trapped with inefficient technologies.

The improvement of EE can bring several benefits, for example decreasing household energy spending and expanding productivity, and so resulting in economic growth, better energy security, and reduced energy demand and environmental stress. According to the 2012 World Energy Outlook, EE has the potential to substantially reduce greenhouse gas (GHG) emissions in the coming decades. In a 2°C temperature increase scenario, EE can contribute to 75% of emissions reductions by 2020 [2]. For developing countries, EE is crucial since it can cut down energy-demand growth, so that the nations require less additional needs to increase power production capacity and can facilitate wider energy access to their citizens. Moreover, improving EE will also reduce energy consumption resulting in lower fossil fuel imports for the countries and higher national energy security.

Low-income households can benefit from EE improvement because they can save on their energy bills and divert their income to satisfy other needs [3]. EE technologies at the household level can have attractive payback periods and could therefore be considered to be a logical choice, although a range of barriers prevents households from investing in these technologies and a lot of potential for EE improvement remains untapped.

Low-income households face several economic and non-economic barriers hindering them from investing in EE. Typically, a low-income household should consume less energy than a high-income household as a higher income is likely to influence an increasing number of appliances and hence appliance energy usage. However, low-income households tend to choose household appliances that are less energy efficient because they are prone to choose products with lowest initial costs, which often are also of low quality and energy inefficient. Wada et al. suggest the reason behind this phenomenon is that the low-income households have low liquidity of available funds, so their opportunity cost for investing in EE technologies is higher than that of other income groups [4]. In other words, they would rather save their household budgets for consumption that is perceived to be more important, possibly education for children or healthcare, than invest in EE improvement.

Given that many household appliances have long lifespans and are often relatively expensive for low-income households, these households are likely to be trapped with low performing appliances for a long time. This path dependency is why proactive policies are necessary to smooth the transition from being low income to middle income, and to assist those households to adopt high-energy efficient technologies before they are stuck with long-term inefficient consumption. Similar studies using socio-economic data of this target group are extensively conducted in developed countries elsewhere, for example, Sweden [5], USA [6, 7], UK [8], Ireland [9], and France [10]. However, there is limited knowledge regarding this particular group in Thailand. Aiming to develop a method to identify this target group in Thailand, this study offers a critical stepping stone for policy study with socio-economic data.

This study examines the energy consumption behaviors of low income households defined as those who (1) have the monthly income between 3,000 baht (around US$ 100/month) to 15,000 baht (US$ 500/month), and (2) have access to electricity to establish a database on household energy use, and to identify the opportunities and barriers to the adoption of EE technologies, measures and policies.

Method

This study carried out household surveys in Thailand between January and May 2014. The surveys were conducted on 293 households spread out in Bangkok and four other rural areas of Thailand; Mae Hong Son, Pat Ta Lung, Surin, and Sra Keaw. The questionnaire was developed to gather characteristic and socio-economic data of these low-income households including their energy consumption, decision-making attributes, awareness and knowledge of EE. Table 1 shows the basic characteristics of the studied sites.

Table 1 Characteristics of the studied sites

<table>
<tr><th>Province</th><th>Part of Thailand</th><th>Number of surveyed households</th><th>Key characteristics</th><th>Population density</th><th>Climate</th><th>Access to electricity</th></tr>
<tr><td>Bangkok</td><td>Central</td><td>93</td><td>Urban poor, mostly in slum areas</td><td>High density</td><td rowspan="5">Tropical climate</td><td rowspan="5">All have access to national grid for more than one year</td></tr>
<tr><td>Mae Hong Son</td><td>North</td><td>50</td><td rowspan="4">Rural parts of the country</td><td rowspan="4">Low density</td></tr>
<tr><td>Surin</td><td>North eastern</td><td>50</td></tr>
<tr><td>Srakeaw</td><td>East</td><td>50</td></tr>
<tr><td>Pattalung</td><td>South</td><td>50</td></tr>
</table>

A non-random sampling strategy was applied because of the novelty of the research, complexity of the topic, and resource constraints. While representative sampling aims to accurately reflect the whole population, (i.e. through random, or probability sampling so that each household has an equal chance of being selected), non-random samples are not generalizable since they imply that some households are more likely to be selected than others. However, the study employed a systematic and stratified sampling plan to increase the robustness of the sampling representation. Outside Bangkok, the study used gross provincial product (GPP)[1] to find provinces with the lowest income level in four parts of the country. The province with the lowest GPP per capita in each part of Thailand was selected as it is more likely to find the target group[2]. Households were selected from the populations that were likely to be low-income households throughout the country.

The design of the questionnaire was by an iterative process based on the research aims and objectives, then discussed and revised amongst researchers and local experts. A pilot survey was launched on 15 households, and a few further revisions were then made afterward. All surveys were carried out face-to-face to encourage a higher response rate and higher quality responses. The final questionnaire had a total of 100 questions, which were divided into three sections as follows.

•*Section A*: The first section aimed to capture the households' basic information about the chief wage earners and other household members including gender, age, education, income, household size and the decision makers in the households regarding energy.

•*Section B*: This section focused on current household energy consumption, both electricity and other fuels. The data collection included usage hours and wattage of all household appliances including amount of appliances owned by households, the age of appliances, and energy aspirations.

•*Section C*: The last section investigated EE, for instance, the importance of different types of information and attributes for making decisions when obtaining additional appliances, and the households' knowledge of EE, especially regarding Thailand's EE label. Many of the household electrical appliances in Thailand have an EE label referred as "Label No.5" issued by the Demand Side Implementation Division of the Electrical Generating Authority of Thailand (EGAT). The label has been operated on a voluntary basis and extended to new appliances since 1993. The labels are applied to some of the household appliances, for example, refrigerators, electric fans, televisions, electric kettles, and rice cookers[3].

The survey included mainly closed questions with multiple choices, but there were some open-ended questions as well to provide respondents with the opportunity to raise any energy-related issues that may have been missing from the questionnaire.

[1] The GPP data used in this study were from The Office of the National Economic and Social Development Board (NESDB) available online at http://www.nesdb.go.th/Default.aspx?tabid=96

[2] It should be noted that Pattani province has the lowest GPP per capita in the southern part of Thailand; however due to the unsafe political situation in the province, the researchers chose to instead conduct the survey in Pat Ta Lung, which is the province with the second lowest GPP in the south. Furthermore, the province with the lowest GPP per capita in the northeast of Thailand is Nong Bua Lamphu. However, this study chose Surin province instead since it is located much closer to Bangkok and cost much less to conduct a survey. In addition, GPP per capita in both provinces is not so different; both are below 40,000 baht/person per year (around 1,250 USD/person per year), which is considered low compared to the rest of the country.

[3] For more information on the Label No.5, please visit its official website at http://labelno5.egat.co.th/index.php?option=com_content&view=article&id=112&Itemid=229&lang=en

Results

Due to the extensive amount of data collected, this publication will only summarize the most relevant results and analyses from sections A, B, and C of the questionnaire. A fully elaborated report will be published at a later stage of the MECON research project[4].

Section A: Characteristics of a low-income household

The respondents in the surveys are mixed in many ways. The majority of the surveyed sample, 168 households or 57% of respondents, is female. Around 57% of participants are the chief wage earners. The average household size is 3.45, and around 60% of the surveyed households have 2-4 family members. The households in Bangkok are slightly smaller with 2.75 household members on the average compared to 3.76 in rural areas. Around half of the family members, or 1-2 persons per household, earn incomes on a regular basis. In rural areas, 152 out of 200 households (76.0%) have monthly income between 3,001-8,000 baht (around 100-250 USD), while 78 out of 93 households (83.9%) in Bangkok have monthly income between 8,001-15,000 baht (251-500 USD).

Most chief wage earners have been educated to primary school level, while the secondary and college/university levels come in second and third. However, the survey data suggest a contrast between households in Bangkok and the other four provinces as shown in Figure 1. A majority of the chief wage earners in rural areas (71.5%) have primary education, while the education levels of those in Bangkok are more evenly distributed between primary, secondary and college/university levels.

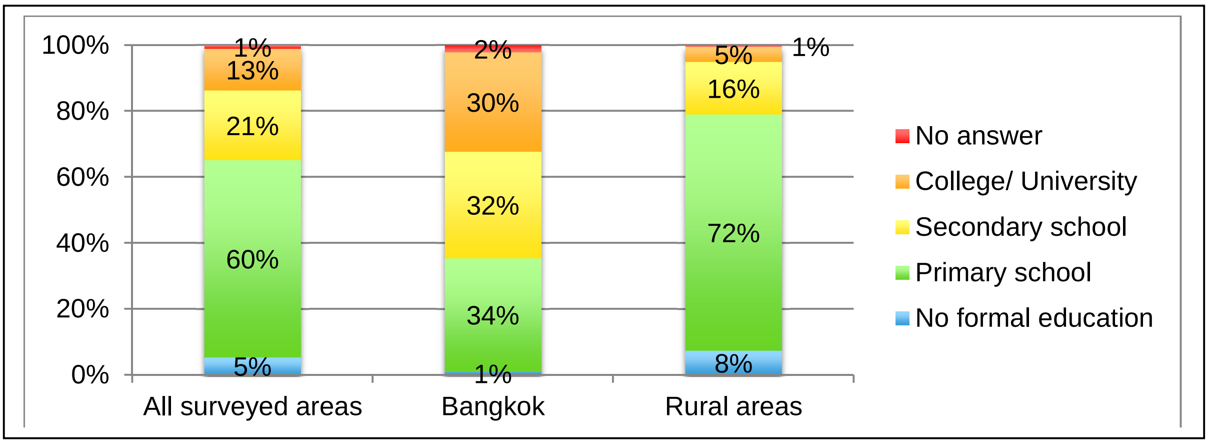

Figure 1 Education levels of the chief wage earners

While agriculture is the most common occupation among the chief wage earners in the rural areas, the occupations of those in Bangkok are more varied, for example, general unskilled labor (employee), street vendor, shop retailer, teacher, professional and working in governmental offices, as presented in Figure 2. This shows the distinction between common occupations in Bangkok and in rural areas.

[4] This study is part of the research project called Effective Energy Efficiency Policy Implementation targeting “new Modern Energy CONsumers” in the Greater Mekong Sub-region (or MECON, in short). For more information, please visit www.meconproject.com

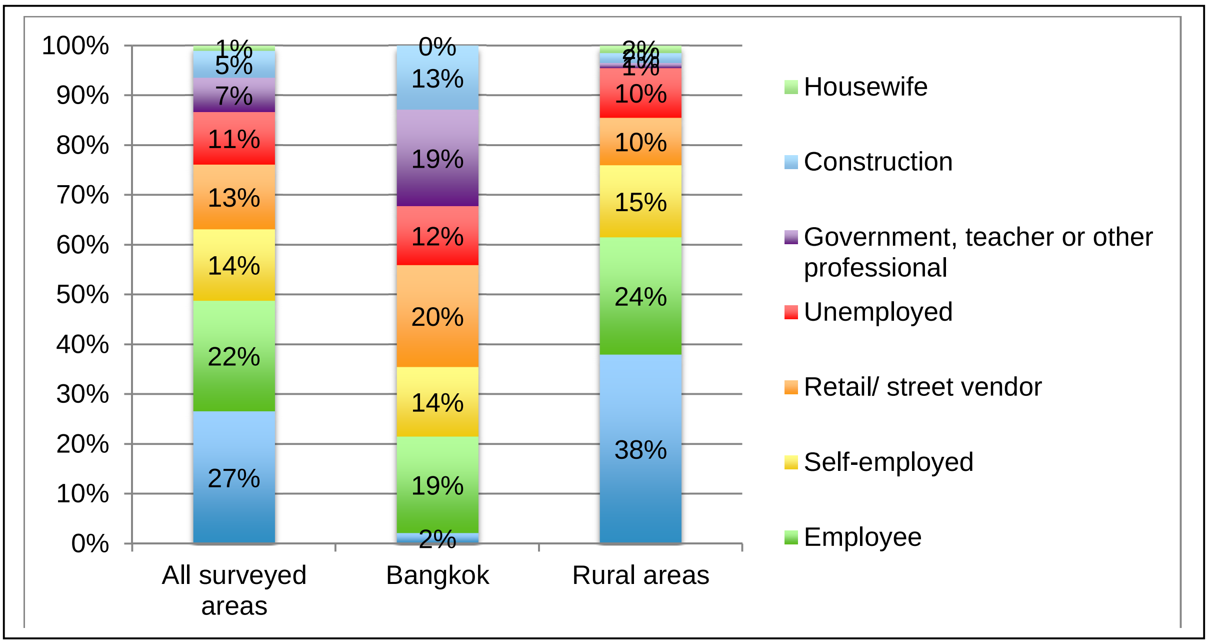

Figure 2 Occupations of the chief wage earners

In terms of decision making on energy, around a quarter of the surveyed households make decisions jointly within the families, while there are almost one third (32%) of the households where female family members make decisions regarding energy as shown in Figure 3. The decision-making on household energy consumption in this case includes the options on both electricity and other fuels consumed in the households, and also takes into account the decisions on the choices of fuel, on energy-consumption patterns within households, and on buying/replacing new appliances.

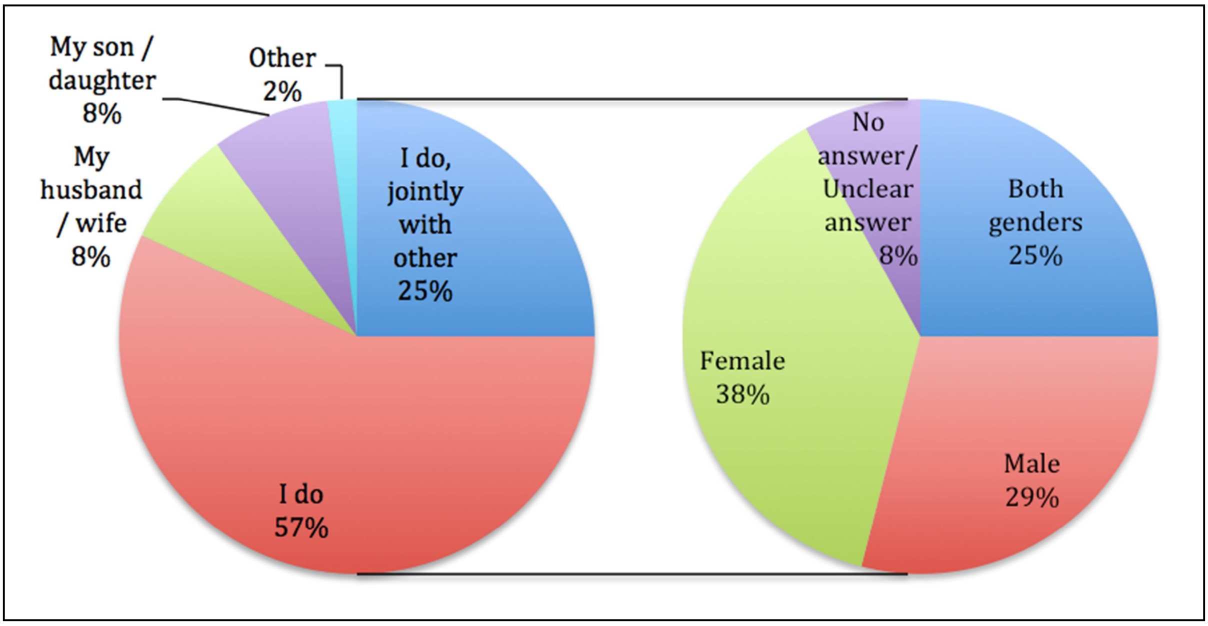

Figure 3 Decision makers regarding household energy consumptions

Section B: Household energy consumption

All surveyed households have access to electricity, and almost all have had access for more than one year. Most of the households (91.4%) are connected to the national grid, while a few are linked to community grids (5.5%) and a small minority has unauthorized access (3.1%).

The survey results suggest several more distinct differences in household energy consumption between Bangkok and the rural areas. The average Bangkok households spend more on energy than their counterparts in the rural areas as shown in Table 2.

Table 2 Household spending and consumption on different types of energy

Average expense and consumption on fuel type	Bangkok	Rural areas
Expense on electricity (baht/month)	790 (24 USD)	374 (12 USD)
Expense on LPG (baht/month)	204 (7 USD)	161 (5 USD)
Expense on charcoal (baht/month)	257 (9 USD)	172 (6 USD)
Consumption of electricity (kWh/month)	243	136
Consumption of LPG (kg/month)	8	7
Consumption of charcoal (kg/month)	17	15

The electricity price in the residential sector of Thailand is set at a progressive rate meaning that the more electricity consumption the higher the price and costs to the consumer. A consumption of 150 kWh per month defines the progressive step separating the cheaper rate from the more expensive one. Approximately 88% of the low-income households in Bangkok consume more than 150 kWh per month, while only 15% of the household in rural areas consume more than this. The low income households in Bangkok tend to consume more electricity than those in rural areas, and thus not only have higher costs due to higher consumption but also higher electricity prices as they exceed 150 kWh per month.

The surveyed households also use other types of fuel, namely, liquid petroleum gas (LPG), charcoal and firewood mainly for cooking purpose, but a lower percentage of households in Bangkok use these fuels regularly than in rural areas. Even though Table 2 suggests that the low-income households in Bangkok consume more energy per household, only 56% of households in Bangkok use LPG regularly as opposed to 86% in rural areas. Similar results are also found in charcoal (11% in Bangkok; 81% in rural areas) and firewood (4% in Bangkok; 54% in rural areas).

This result is consistent with the rate of owning cooking appliances. According to the surveys, a lower percentage of households in Bangkok own cooking devices (LPG stove, biomass cooking stove, and rice cooker) than the percentage of households in rural areas as presented in Figure 4. None of the households own an efficient biomass cooking stove and kerosene stove, and less than 5% of the households have an electric hot plate and microwave oven.

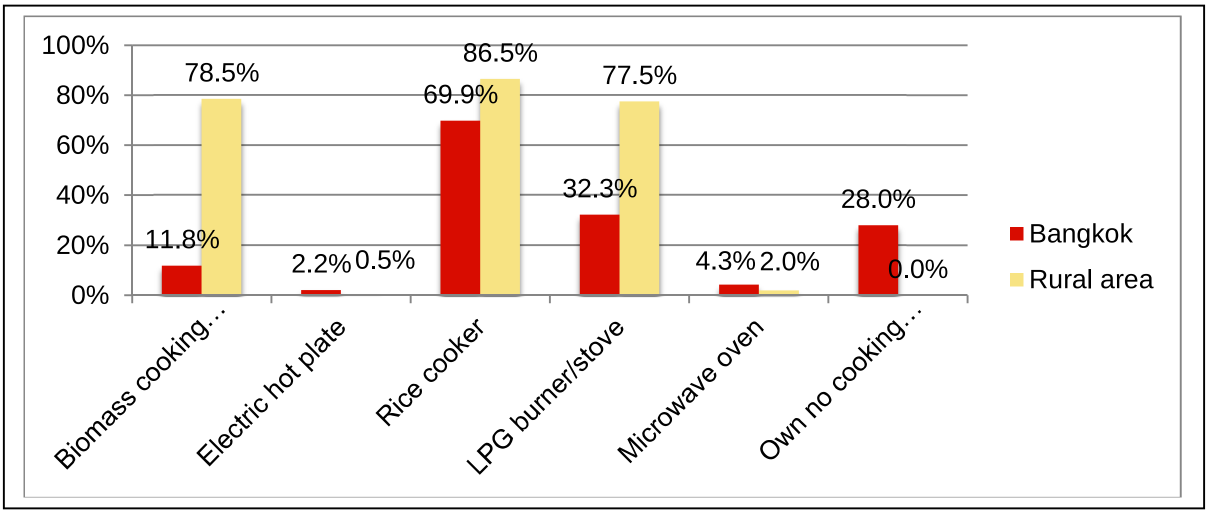

Figure 4 Rates of owning cooking appliances

There are vast differences in the rate of owning cooking appliances between the low-income households in Bangkok and those in other rural provinces. In fact, the survey reveals that 28% of the households in Bangkok do not own any cooking appliances at all, while all of the households in the other four provinces have at least one cooking appliance. Moreover, 30% of the households in Bangkok own only rice cookers, while only 5% of the households in the rural areas own only rice cookers. This suggests that the cooking activity of low-income households in Bangkok should be far less than in the other four provinces; this is further discussed in the last section of this paper.

Regarding lighting appliances, fluorescent lamps dominate over compact fluorescent lamps (CFLs) among the surveyed households, while less than 5% of the households use incandescent lamps, and none use the light emitting diode (LED) lamp. Moreover, none of the households use car batteries or a kerosene lamp for lighting purpose. Figure 5 shows a comparison of the rates of owning different lighting technologies from the survey data.

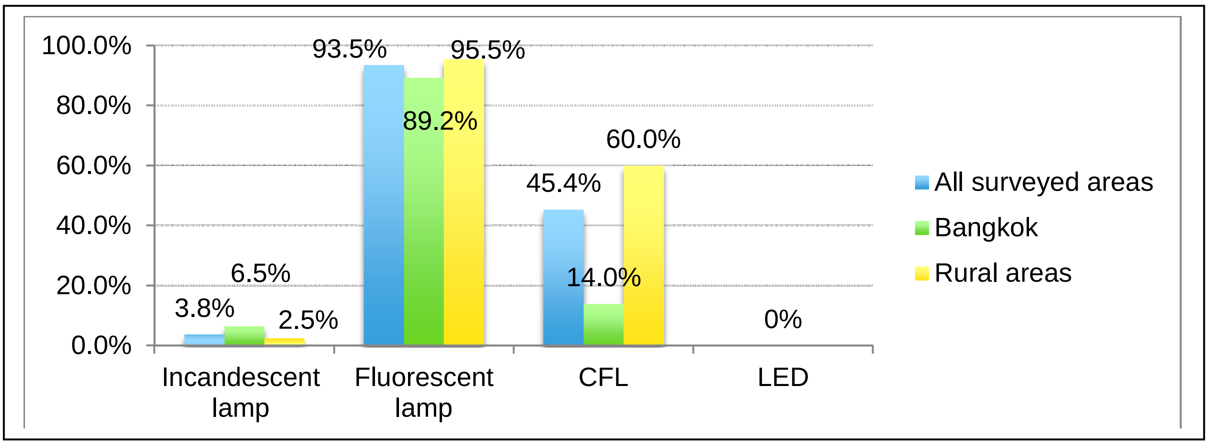

Figure 5 Rate of owning by lighting types and surveyed areas

CFLs are more widely used in rural provinces (60%) compared to Bangkok (14%). It is not clear from this survey why the rate of owning CFL in rural areas is higher than that for Bangkok, and more studies should be conducted to further investigate this issue.

Regarding the energy consumption of each appliance, this study collected data on wattages and daily hours used of all appliances owned by the households. With these data, we calculated that the total electricity consumption of all 297 surveyed households is approximately 463,510 kWh per year, costing 1,390,530 baht (around 46,350 USD) per year assuming the electricity price is 3 baht/kWh. Table 3 shows the calculation results of the top five energy-consuming appliances including air conditioning (AC) units and washing machines.

Table 3 Estimated electricity consumption and costs of some appliances

Appliance	**Owning rate**	**Annual electricity consumption (kWh/year)**	**Percentage of electricity consumption**	**Electricity cost (baht)**
Rice cooker	81.2%	85,224	18.4%	255,672 (8,522 USD)
Fluorescent lamp	93.5%	75,914	16.4%	227,742 (7591 USD)
Refrigerator	78.5%	64,844	14.0%	194,532 (6,484 USD)
Electric fan	90.8%	54,205	11.7%	162,614 (5,420 USD)
Electric kettle	39.3%	51,904	11.2%	155,711 (5,190 USD)
Air Conditioning unit	3.1%	24,631	5.3%	73,893 (2,463 USD)
Washing machine	42.7%	5,374	1.2%	16,123 (537 USD)

In addition to the top five most energy consuming appliances, we show the results for air conditioning (AC) units and washing machines because these two appliances are usually believed to contribute to a large share of household energy consumption. However, the result shows that this is not the case, where many small appliances, i.e. rice cooker, fluorescent lamp, electric fan, or electric kettle, may consume more electricity in total (kWh/year) than large appliances, such as, AC units, or washing machines. It should be noted that there are only nine AC units found among the surveyed households (owning rate=3.1%). Hence, an AC unit still has the highest energy consumption power rating per item, but it is not the most energy-consuming appliance among this target group. A discussion on this result will be presented in the last section of the paper.

Section C: Energy efficiency

The questionnaire in this study was also designed to capture the percentage of the appliances with Thailand's Label No.5 from all surveyed appliances owned by the households as shown in Figure 6.

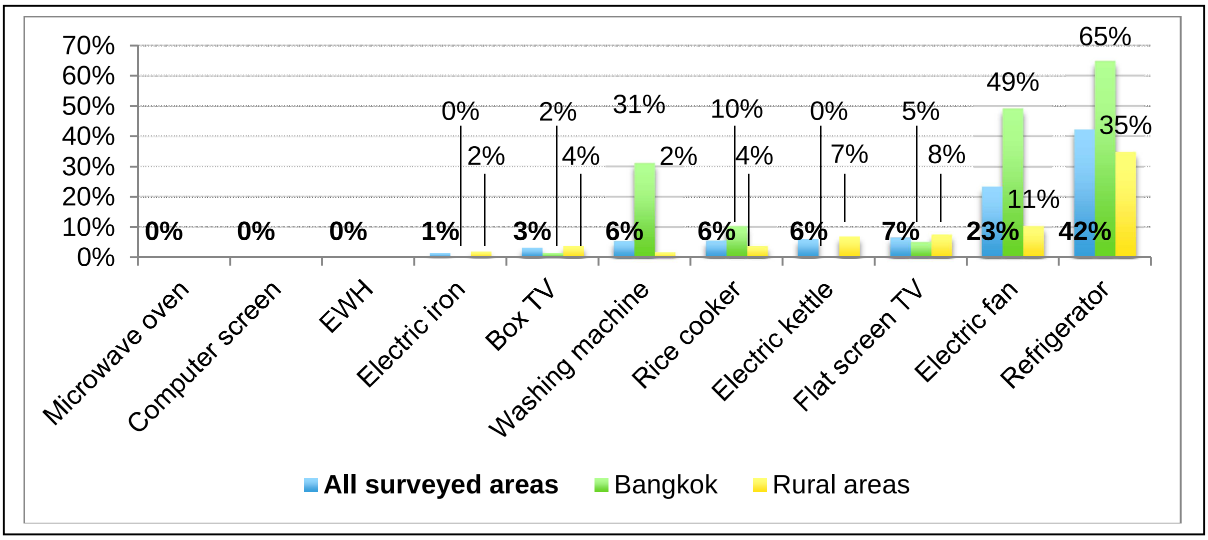

Figure 6 Percentage of appliances with Thailand's No.5 EE Label (EWH = electric water heater)

Although the No.5 label has been well known for many years, it seems to only have a modest impact among this target group. Only 42% of refrigerators and 23% of electric fans owned by the households have the label, while the adoption rates of other appliances are very low (less than 10% or none). The adoption rates of some appliances with EE labels, for example, refrigerator, electric fan, rice cooker, and washing machine, are higher among the households in Bangkok than in rural areas. Around two third of the refrigerators and half of the electric fans found in the households in Bangkok have the labels. This might be it due to lack of access to appliances with the labels in rural areas.

One of the presumptions drawn from the low adoption rate of appliances with the EE label is the claim that low-income households have little awareness and knowledge of the No.5 label. The respondents were also shown the No.5 label, and then asked if they had ever seen the label before and if they knew what the label represented. The result is shown in Figure 7.

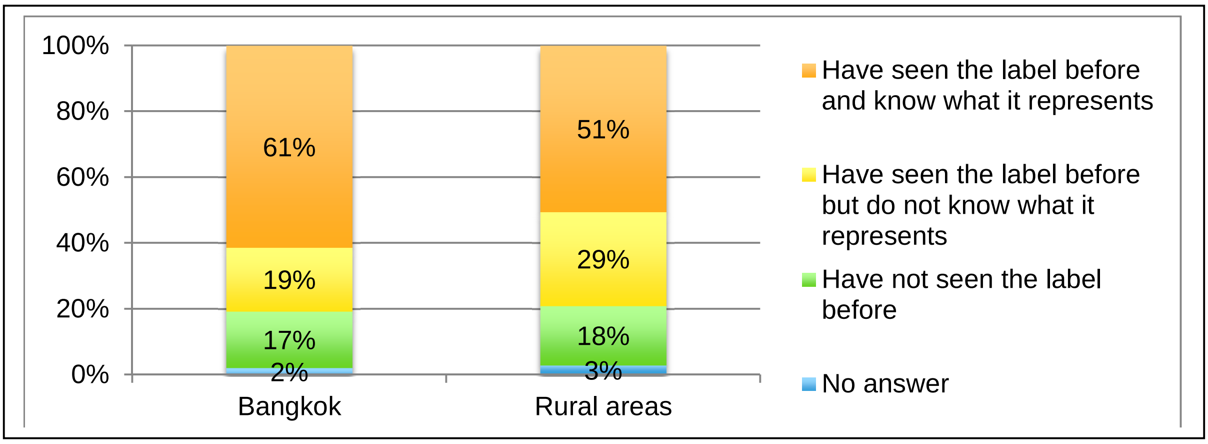

Figure 7 Awareness of the surveyed households of the No.5 Label

The result shows that the label seems to be well known among this target group. Around 80% of all respondents have seen the label before, even though only 61.3% of the respondents in Bangkok and 50.5% of those in rural areas know what it represents.

Discussion

Policies designed to raise awareness and knowledge of EE should focus on primary education in particular because it is the main education level among the chief wage earners of this target group (Figure 1). Also, these policies could help these households to decrease their illiteracy on Thailand's Label No.5 as the survey result suggests there is room for improvement in that area (Figure 7). However, chief wage earners are not necessarily the ones who make decisions regarding energy in the households. Many households select energy choices and patterns of consumption jointly with other household members. A policy design on decision-making tools could especially target female household members since they are more likely to be the ones who make decisions on energy in the households (Figure 3).

The challenges of designing policy interventions to improve EE of Thailand's residential sector are the substantial differences between urban and rural areas. Many observations from this study show distinct differences between the households in Bangkok and those in the four other provinces. In general, the low-income households in Bangkok are more likely to consume more energy per household, both as electricity and as cooking fuels, than those in rural areas (Table 2). However, the study suggests that cooking activities of the households in Bangkok seem to be far less than the counterparts in rural areas. This results from lower rates of owning cooking appliances (Figure 4), and less regular use of cooking fuels among the households in Bangkok in comparison to this in the rural areas.

Presumably, people in Bangkok may prefer or be accustomed to ready-to-eat meals or street foods, and therefore, do not use cooking fuels regularly and do not need cooking appliances. Many of them may cook only their own rice and buy other foods from outside, which is a common lifestyle in the urban areas, explaining why around 30% of the households in Bangkok have rice cookers as their only cooking appliance. On the other hand, cooking is a part of daily life in rural areas where many ingredients can easily be found in agricultural lands nearby. Cooking can be a crucial cost saving for those in the rural areas. Furthermore, time constraint could be another crucial factor in these differences. Many people living in the city spend their time commuting and working in a rush, thereby cooking may be too much of a burden, and buying foods is an inevitable choice especially for those with low incomes and limited choices in their lives. In contrast, the lifestyle in rural areas moves at a slower pace, and cooking is a choice that is more available compared to the urban areas. Nevertheless, these differences in cooking activities should be further investigated.

Since the low income households in Bangkok may have purchased cooked meals from food stalls, supermarkets, or other sources, the energy consumption for cooking may be hidden in other sectors, and further research could focus on this indirect household energy consumption that could be significantly large among this target group in urban areas. In conclusion, cooking activity and its energy consumption are another distinction between Thailand's urban and rural areas of which policy makers should be aware. An overgeneralization could lead to adverse results or ineffective policy implementations.

The study also finds that Thailand has been successfully phasing out inefficient incandescent light bulbs to a very low owning rate among these households (shown in Figure 5). While fluorescent lamps are the most dominant lighting technology among the surveyed households, CFLs and LED lamps are not as widely adopted. As shown in Table 3, fluorescent lamps contribute a large share of energy consumption. In conclusion, lighting technologies with higher efficiency still need some policy push to help them penetrating the low-income households, and there are opportunities for EE improvement in these technologies.

Appliances contributing to the largest share of annual electricity consumption do not necessary have to be large appliances with high wattage, namely, AC units or washing machines (Table 3). On the contrary, small appliances, such as rice cookers, fluorescent lamps, electric fans, and electric kettles, can consume more electricity in total because of high owning rates, large numbers per household, and long hours of use per day. Hence, policy makers should not neglect these small appliances since they are more common among this target group. Moreover, only 3% of the surveyed household own AC units, thereby it is not the most energy consuming appliance among this target group. However, if we assume that this target group will earn more income and start owning more AC units in the near future, policy makers should consider measures that can raise the adoption rate of AC units with high efficiency in this particular group.

Regarding Thailand's No.5 EE Label, the result shows that appliances with the label have not been widely adopted among this target group, though a majority of the respondents already have moderate knowledge and awareness of the label and EE (Figure 6 and 7). Therefore, the reason behind the low adoption rate of appliances with the label among this target group seems not to come from lack of knowledge and awareness alone, but from other barriers, for example, financial constraints or the ready availability of the EE appliances. The effectiveness of the label is low among this group, and policy makers should develop a complementary strategy to penetrate this target group in addition to just simply raising awareness of the label. Since low-income households are supposed to have the largest financial barrier in comparison to wealthier groups, they tend to adopt EE technologies the least and latest. Further investigation should explore the financial barriers faced by these households including willingness to pay for higher efficient technologies among this group in order to design appropriate financial supports or other policies.

Seemingly, the higher initial costs of appliances with the label may be more difficult to absorb by this target group. Policy makers should improve the adoption rate of appliances with labels, or should develop other strategies to help low income households to realize the benefits of the label. A special emphasis could be on rice cookers, electric fans, and refrigerators given that all of them have owning rates higher than 75%, yet only a few of these appliances have Labels No.5 (Table 3 and Figure 6). Moreover, the adoption rates of the appliances with the label are higher among the households in Bangkok than those in rural areas, especially, refrigerators, electric fans, rice cookers, and washing machines. This means that these appliances may have been successfully promoted in Bangkok, but not so much in other areas. Further research should explore the reason behind this as well.

Conclusion

Thailand and many other countries lack data on energy consumption in the residential sector. Household surveys such as this study could be very beneficial for raising awareness, and for designing effective policies to improve EE. Similar studies should be conducted with larger sample size and should be extended to other income levels. Moreover, the data collection needs to be conducted continuously to capture long run trends. In the broader discussion of policies toward sustainable energy for all, studies on the socio-economic data in the residential sector are also recommended for other developing countries, especially in the CLMV countries (Cambodia, Laos PDR, Myanmar and Vietnam) where the industrial sectors are not fully developed and the residential sector consumes the most energy. An EE improvement can be achieved through implementing an appropriate set of policies, but the financial and policy resources are often scarce in these countries. This is why socio-economic data could play a crucial role in designing effective policies and improving EE. Encouraging EE can also help these countries to conserve fiscal budgets and allow governments to focus on expanding electricity accessibility rather than building new power plants just to keep up with the fast growing demands from the emerging middle class in this region.

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Efficiency categories for household electricity consumption as a new approach to initiate reduction measures in German households

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Abstract

Household electricity consumption in Germany was rather stable in the last years. Despite the fact that the energy efficiency of household appliances and other devices typical for households (e.g. televisions, computers) as well as lighting significantly increased, a significant reduction in electricity consumption could not be observed. Against this background the targets of the German Government to reduce gross electricity demand by 10 percent in 2020 based on 2008 are unlikely to be achieved in the household sector.

In Germany a number of online tools exist where consumers are able to check their electricity consumption by entering specific data on their household. As some of these tools are in use for quite some time now, a considerable amount of consumer data could be gathered and analysed.

Based on these analysed data a categorization system for the electricity consumption of households was developed that distinguishes between 20 different household types with four different consumption levels (from low to high consumption). The differentiation was done according to the number of persons in the household, reaching out from 1 person- to a maximum of 5 person-households. New in the approach is to also distinguish whether people are living in a flat or in a house and whether electric water heating exists or not.

Background

The electricity saving initiative in Germany ("Die Stromsparinitiative")

The German Federal Government has set the target to reduce electricity consumption by 2020 compared to 2008 by ten percent. By 2050, consumption should be reduced as much as 25 percent. In addition to the phasing out of nuclear energy and the development of renewable energies, the energy transition in Germany ("Energiewende") mainly addresses the improvement of energy efficiency. The aim of the electricity saving initiative of the German Federal Environment Ministry is to motivate as many private households in Germany as possible to use their potential for energy savings and reduce electricity consumption. This way not only households can reduce their energy costs in the long term. Also the climate benefits from energy savings, and Germany's dependence on imported energy decreases.

The electricity saving initiative is supported by the participants of the roundtable that come from different sectors of society to support the Federal Environment Ministry with their expertise. It is beyond the scope of this paper, to name all the partners, but they can be found on www.die-stromsparinitiative.de, the website of the electricity saving initiative.

Within the framework of the electricity saving initiative it was the aim to develop the German electricity tables, a categorization of German household electricity consumption that gives consumers orientation and motivates them to save energy.

The research project “Electricity efficiency classes for households”

To date there have only been energy efficiency classes for individual appliances such as washing machines. However, these labels supply no information about how much electricity is actually being consumed when an appliance is in use. The total electricity consumption of a household is also an unknown entity – for example per day, week or year, depending on behaviour patterns. This is the starting point of the project “Electricity efficiency classes for households”, with the goal of developing an indicator for households so that they can more easily estimate their total power consumption and better implement specific goals for saving power. Electricity efficiency classes for households might include classes A–F like the energy label of the European Union or classes 1-7. It is based on the annual electricity consumption of a household, extended by attributes like household size. The research project "Electricity efficiency classes for households" is carried out by the Institute for Social-Ecological Research (ISOE) and the Öko-Institut. The website of the project is: www.stromeffizienzklassen.de

Studies on electricity consumption in German households

To take advantage of the potential savings still existing in many households, information and advisory services are as important as the communication of meaningful comparison values. Against this background it was the aim of the work presented here to develop electricity tables for Germany that allow consumers to compare their electricity consumption with the one of similar households. Subsequently they will be able to classify their consumption as "little", "low", "medium" or "high" on the basis of their own electricity bill. Individual factors such as household size, type of building or the type of water heating should be included in the result and allow a differentiated evaluation of one's own electricity consumption.

The following studies on power consumption and supplies in German households have been considered in the preparation of the current electricity tables:

Table 1: Overview of studies on electricity consumption in German private households

Title, source	Publisher, basic year(s)	Data origin	Description
"Household energy consumption", selected results of the study on energy use in households [1]	BDEW and HEA, 2009	forsa	Survey of about 3,000 households of the forsa panel
"Where in the household remains the electricity? – Shares, consumption and costs differentiated by 12 consumption areas in one to six-person households " [2]	EnergieAgentur.NRW, 2011	own survey	Evaluation of electricity consumption data from 380,000 households, based on: results of the electricity checks for households of EnergieAgentur.NRW
"Electricity consumption by application purposes in households" [3]	HEA, BDEW, EnergieAgentur.NRW, 2012	Research institute EEFA in Münster	Evaluation of 450,000 records of current online checks for households of EnergieAgentur.NRW
Survey studies on energy consumption [4], [5]	BMWi, 2006 - 2010	RWI and forsa	Representative sample survey, based on the forsa panel of approximately 10,000 households
BMUB ElectricityCheck [6]	BMUB, 2012 - today	Online tool to benchmark the level of power consumption	Differentiation by household size, water heating, building type, cast. 110,000 records
dena Guide on efficiency in electricity consumption (Online Guide) [7]	DENA, 2009 - today	Online tool for electricity saving	Differentiation by household size, water heating, building type. Currently no data is stored.
co2online ElectricityCheck-Express [8]	co2online gGmbH, 2010 - today	Online tool to benchmark the level of electricity consumption	Differentiation by household size, water heating, a total of 110,000 records

Abbreviations: BDEW: German Association of Energy and Water Industries (Bundesverband der Energie- und Wasserwirtschaft); HEA: Fachgemeinschaft für effiziente Energieanwendung e.V; EnergieAgentur.NRW: EnergyAgency.NRW (NRW: North Rhine Westfalia); EEFA: Energy Environment Forecast Analysis; BMWi: German Federal Ministry for Economic Affairs and Energy; RWI: Rheinisch-Westfälisches Institut für Wirtschaftsforschung; BMUB: German Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety; dena: German Energy Agency (Deutsche Energie-Agentur GmbH).

Methodology

Data set used for the electricity tables

The current electricity tables for Germany ("Stromspiegel") is the result of a broad social alliance of consumer organizations, trade associations, energy agencies and research institutions. It takes into account all the relevant data surveys and studies on electricity consumption in Germany and merges them with a consistent methodology. Consolidation and alignment of the different data sources were carried out by the Öko-Institut and co2online, based on the findings of the electricity saving initiative and the current check.

The following project partners have their own data, which were used for the preparation of the current electricity tables:

- BDEW German Association of Energy and Water Industries. V.
- Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Construction
- co2online gGmbH
- VKU German Association of Local Utilities e. V.
- Verbraucherzentrale Energieberatung (energy consulting of consumer advice centre)

In addition, the data of the Energy Agency NRW and the German Energy Agency have been included as comparative value.

Only the data collected on the basis of the online tools ElectricityCheck and ElectricityCheck Express (see above in table 1) were differentiated enough to serve as a basis for the electricity tables at the moment: household size, water heating with and without electricity and the Building Size (one- and two-family house or apartment in an apartment building).

The data provided by co2online and BMUB consist of the anonymised records of the online tools ElectricityCheck and ElectricityCheck Express. In both checks consumers enter data on their household and on their electricity consumption that will then be evaluated. For the electricity tables for Germany about 110,000 relevant records, collected in the past two years have been considered from these two online tools. Prior to the evaluation, the input made in the tool by consumers was checked for plausibility and data were adjusted where necessary.

The wide range of electricity consumption in German households requires a detailed differentiation of consumers resp. households. Besides the number of persons in the household, the following factors are decisive for the level of electricity consumption and accordingly differentiated in the current electricity tables:

- Water heating with or without electricity: When the desired water temperature is generated by electricity the electricity consumption of a household increases by 28 percent. Almost one third of all households in Germany is affected.
- Distinction between flat and one- and two-family house: The electricity consumption in a flat in a multi-family house tends to be lower than that in a one- or two-family house. Reason for this is extra electricity consumption in one- or two-family houses for exterior lighting, garden, garage, or electricity for heating pumps (not shared).
- Differentiation between high, medium, low and little consumption

The data analyses delivered by BDEW and Verbraucherzentrale Energieberatung (consumer advice centre energy consulting) contained only one of the above mentioned distinctive features. Therefore they were not included directly in the data base for the electricity tables. But these data were used as comparative value for the data of co2online.

Classification of Categories for the electricity tables

Based on 110.000 relevant data sets of consumption values from ElectricityCheck and ElectricityCheck Express a categorization was developed that refers to the quantiles of the distribution of the consumption values. The aim was to define the categories in a way that they are straightforward, which led to only four different classes from “little” to “high”. The second aim was to define the width of the classes in a way that they would still motivate consumers to save energy and to try to switch classes. Against this background the four categories of the electricity tables are defined as follows:

- Category “little”: 0-12.5% of the distribution of electricity consumption.

- Category “low”: 12.5 to 37.5% of the distribution of consumption.
- Category “medium”: 37.5 to 62.5% of the distribution of consumption.
- Category “high”: 62.5 to 100% of the distribution of consumption.

Intentionally, the categories left of the mean value are kept smaller, e.g. in the category “little” 0-12.5% of the distribution is included compared to 62.5% to 100% in the category “high”. That way consumers shall be kept motivated to save electricity and to make a shift between categories with already relatively low electricity consumption, e.g. from “low” to “little” even if the absolute saving potential is significantly lower than for households belonging to the category “high”.

The division into consumption categories was done in collaboration with the research project "Power efficiency classes for households" which is carried out by the Institute for Social-Ecological Research (ISOE) and the Öko-Institut. In comparison to the electricity tables, the electricity consumption is further divided in subclasses, precisely in the efficiency classes from 1 to 7: category “little” corresponds to efficiency class 1; category “low” corresponds to efficiency classes 2 and 3; category “medium” corresponds to efficiency classes 4 and 5; category “high” corresponds to efficiency classes 6 and 7.

Results

The German electricity tables (“Stromspiegel”)

For each of the 20 different household types defined by building type, way of water heating and number of persons per household the consumption values were specified that establish the border between the four categories “little” to “high”. Additionally the mean value for each of the 20 household types was determined. The following table shows all the values.

Gebäudeart	Personen im Haushalt	Verbrauch in Kilowattstunden (kWh) pro Jahr				
		Gering	Niedrig	Mittel	Hoch	Mittelwert
Ein- oder Zweifamilienhaus, Warmwasser ohne Strom	1	< 1.500	1.500 – 2.200	2.200 – 3.200	> 3.200	2.700
	2	< 2.100	2.100 – 3.000	3.000 – 3.600	> 3.600	3.200
	3	< 2.700	2.700 – 3.500	3.500 – 4.300	> 4.300	4.000
	4	< 3.000	3.000 – 4.000	4.000 – 5.000	> 5.000	4.400
	5+	< 3.500	3.500 – 4.900	4.900 – 6.000	> 6.000	5.500
Ein- oder Zweifamilienhaus, Warmwasser mit Strom	1	< 1.700	1.700 – 2.600	2.600 – 3.700	> 3.700	3.100
	2	< 2.500	2.500 – 3.500	3.500 – 4.400	> 4.400	3.900
	3	< 3.300	3.300 – 4.300	4.300 – 5.600	> 5.600	5.000
	4	< 3.600	3.600 – 5.000	5.000 – 6.200	> 6.200	5.600
	5+	< 4.500	4.500 – 6.300	6.300 – 8.500	> 8.500	7.200
Wohnung im Mehrfamilienhaus, Warmwasser ohne Strom	1	< 800	800 – 1.300	1.300 – 1.700	> 1.700	1.500
	2	< 1.400	1.400 – 2.000	2.000 – 2.500	> 2.500	2.200
	3	< 1.800	1.800 – 2.600	2.600 – 3.300	> 3.300	3.000
	4	< 2.000	2.000 – 3.000	3.000 – 3.800	> 3.800	3.400
	5+	< 2.300	2.300 – 3.600	3.600 – 4.700	> 4.700	4.100
Wohnung im Mehrfamilienhaus, Warmwasser mit Strom	1	< 1.200	1.200 – 1.800	1.800 – 2.400	> 2.400	2.000
	2	< 2.000	2.000 – 2.800	2.800 – 3.500	> 3.500	3.200
	3	< 2.800	2.800 – 3.900	3.900 – 4.700	> 4.700	4.200
	4	< 3.100	3.100 – 4.400	4.400 – 5.500	> 5.500	5.000
	5+	< 3.800	3.800 – 5.500	5.500 – 7.000	> 7.000	6.000

Figure 1: The German electricity tables ("Stromspiegel") published in November 2014 (translation of the legend see below)

Source: [9]. Translation of the legend: 1st column: title: type of building; from top to bottom: one- or two-family house, water heating without electricity; one- or two-family house, water heating with electricity; flat in multi-family house, water heating without electricity; flat in multi-family house, water heating with electricity. 2nd column: title: persons per household. 3rd to 7th column: title: consumption in kilowatt-hours (kWh) per year; 3rd column: little. 4th column: low. 5th column: middle. 6th column: high. 7th column: mean value.

Communication of the German electricity tables

In order to achieve the aim to motivate consumers to save electricity the German electricity tables were then prepared for publication in a brochure available as electronic and printed version. The brochure includes instructions for consumers and links where to find additional information on electricity savings. It was important to stress in the brochure that it is very easy to use the tables for consumers ("In just three steps …") and to benefit in the sense of energy saving as well as money saving. Consumers only need to check their electricity bill and compare their consumption on the bill with the categories in the electricity tables in order to identify savings potentials. The brochure with the German electricity tables was then broadly communicated by the electricity saving initiative (www.die-stromsparinitiative) and their partners (see above). Additionally a media cooperation with Spiegel Online, a very important news portal in Germany, supported the broad dissemination. The publication started on 26th of November 2014. In print, the message recorded 1,112,669 million ad impressions after a week. Until January 2015 the message of the electricity tables overall had been adopted online by more than 300 media, portals and websites.

Subsequently the usage of the ElectricityCheck BMUB, which is presented prominently in the brochure as well as on www.die-stromsparinitiative, increased significantly. In the following figure the number of consultations is illustrated for the months July 2014 to January 2015.

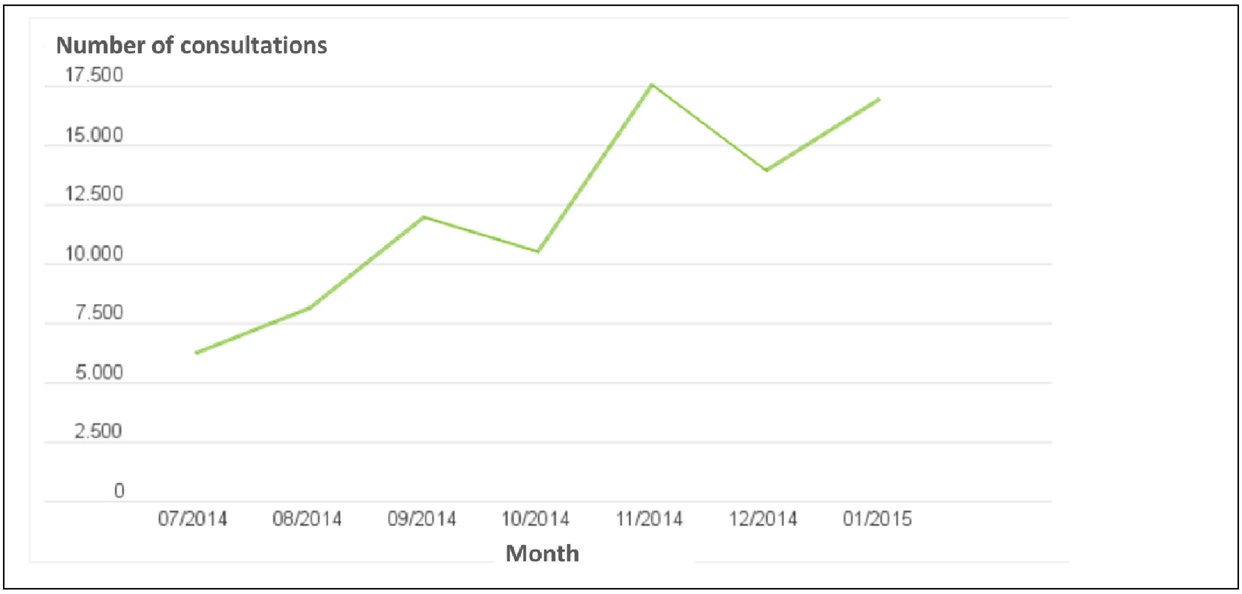

Figure 2: Usage of the ElectricityCheck BMUB from 7/2014 to 01/2015. The electricity tables were published on 26th of November 2014

Source: [10]

Evaluation of the Electricity Check BMUB

Basing on a study from 2013 [11] in the following the results of the evaluation of the ElectricityCheck BMUB are briefly discussed. The evaluation of the ElectricityCheck was made on the basis of an online survey of ElectricityCheck-users with a questionnaire easy to understand. 491 users of the ElectricityCheck were contacted. The response rate was 27.5 percent overall and 14.7 percent for the completed questionnaires. The results showed that 83 percent of users said they want to identify meaningful power-saving measures for their respective household. For 71 percent the audit of the own consumption was crucial. Of the surveyed users, 78 percent have implemented measures. 56 percent of respondents planned (further) measures. 64 percent of users have implemented accordingly energy-saving behavior, 46 percent of old household appliances replaced with energy efficient and 10 percent have even carried out measures on building level. Only 14 percent of respondents do not plan any action. On average, respondents implement 8.3 measures. Thus the results of the evaluation showed that the ElectricityCheck indeed motivates consumers to implement power saving measures.

Electricity efficiency classes for households

Within the project “electricity efficiency classes for households” it was decided to use more different categories than in the electricity tables: seven instead of four efficiency classes were generated. The reason behind was the idea that consumers are more motivated to save electricity if the barriers to reach a better efficiency class are relatively small especially for households that already gained a middle to low consumption level. The following table shows the power efficiency classes for households published in 2014.

Gebäudetyp	Warmwasserbereitung	Personen	max. Verbrauch in kWh pro Jahr						
1–2 Familienhaus, Reihenhaus oder Doppelhaushälfte	mit Strom (elektr. Boiler, Durchlauferhitzer etc.)	1	1.700	2.200	2.700	3.100	3.700	4.500	über 4.500
		2	2.500	3.000	3.500	4.000	4.400	5.000	über 5.000
		3	3.300	4.000	4.300	5.000	5.500	6.500	über 6.500
		4	3.600	4.300	5.000	5.600	6.200	7.300	über 7.300
		5	4.500	5.400	6.000	7.000	8.000	9.700	über 9.700
	ohne Strom	1	1.400	1.900	2.200	2.600	3.100	3.700	über 3.700
		2	2.200	2.500	3.000	3.200	3.600	4.000	über 4.000
		3	2.700	3.200	3.500	4.000	4.200	4.800	über 4.800
		4	3.000	3.600	4.000	4.400	4.900	5.500	über 5.500
		5	3.500	4.200	4.800	5.300	6.000	7.000	über 7.000
Wohnung im Mehrfamilienhaus	mit Strom (elektr. Boiler, Durchlauferhitzer etc.)	1	1.200	1.500	1.800	2.000	2.400	3.000	über 3.000
		2	2.000	2.500	2.900	3.200	3.500	4.000	über 4.000
		3	2.800	3.500	3.900	4.200	4.800	5.400	über 5.400
		4	3.200	4.000	4.500	5.000	5.500	6.500	über 6.500
		5	3.800	4.600	5.600	6.100	7.000	8.000	über 8.000
	ohne Strom	1	800	1.000	1.200	1.500	1.700	2.000	über 2.000
		2	1.400	1.700	2.000	2.200	2.500	2.900	über 2.900
		3	1.800	2.200	2.500	3.000	3.300	3.700	über 3.700
		4	2.000	2.400	2.800	3.300	3.700	4.000	über 4.000
		5	2.300	3.000	3.500	4.200	4.600	5.300	über 5.300
		Ihre Stromklasse →	1	2	3	4	5	6	7

Figure 3: Electricity efficiency classes for households published in 2014 (translation of the legend see below)

Source: [12].Translation of the legend: 1st column: title: type of building; from top to bottom: one- or two-family house; flat in multi-family house. 2nd column: title type of water heating; from top to bottom: water heating with electricity; water heating without electricity; water heating with electricity; water heating without. 3rd column: title: persons. 4th to 10th column: title maximum consumption in kWh per year.

Conclusions and Outlook

Conclusions

In Germany no representative data on household electricity consumption are available that are directly measured in private households and reflect the diversity of household types (e.g. number of persons per household, building type, type of water heating etc.). Against this background, the work presented here showed that as an alternative to the missing measured data, records from online tools like ElectricityCheck can be used as bases to develop consumption categories resp. efficiency categories for German private households' electricity consumption. In order to do so a sufficiently high number of data sets must be available that is differentiated enough to reflect the existing diversity in households.

The work also showed that a broad social alliance in the process helped in two ways: on the one hand, it helped to collect the already available data from surveys and online tools as well as to use them – if not as data sets themselves – at least for a quality check and affirmation purposes. On the other hand, the broad social alliance helped then to disseminate the completed electricity tables to consumers and to energy consultants in order to use them as a mean to motivate people to save electricity. This way the overall targets of the German Government to reduce gross electricity demand will be supported by the German electricity tables as well as by the power efficiency classes for households.

Outlook

It is planned to update the German electricity tables annually on the bases of current records from online tools, e.g. the ElectricityCheck by BMUB. Beyond that it is the aim to broaden the number of tools that deliver data sets for the electricity tables compared to the first version of the electricity tables in 2014.

Concerning the research project “electricity efficiency classes for households” further research will be done on the potentials of the approach of efficiency classes. In October 2014 a field test was started: The project partners started to test the power efficiency classes and corresponding power saving packages in selected households in cooperation with the participating power companies. They will evaluate the households’ sensitisation for their own power consumption and the suitability for everyday use of the various power saving packages. From the results gained, the researchers will develop an optimised version of the total approach whose acceptance is tested with the help of a representative survey with an integrated conjoint-analysis. Afterwards, the team will extrapolate electricity saving potential and transformation effects that can be attained across Germany.

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Appliances

On the Impact of Lighting on Energy Efficiency of Electrical Domestic Appliances

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Abstract

Lamps are widely used integrated in domestic appliances. They are illuminating the interior spaces and working areas. Lighting makes appliances functional, safe and convenient. Special care is on persons with low vision ability, especially elderly people. Sometimes illumination is supporting special features also. Lighting provides aesthetical appearance. At first glimpse the energy consumption of the lamps seems to be rather small and even negligible when comparing it with the overall energy consumption of an appliance. But it is a relevant contribution. Thus manufactures are introducing more efficient lamps and new concepts, mainly based on LED techniques.

Regulatory measures and standards on lamps are affecting household appliances as well. EU regulations (EU) No 244/2009 and (EU) No 1194/2012 on ecodesign are largely exempting household appliances as they are using "special lamps" which not primarily do illumination of the room. However a new project to amend these regulations will aim towards stricter requirements. Furthermore new EU Regulations (EU) No 65/2014 and (EU) No 66/2014 for the range hoods are setting energy limits and are requiring energy performance to be declared at the label.

This paper is analyzing the impact of innovations from the lighting industry which have happened in the past years. It includes a review of the recent developments in the area of household appliances. A somewhat in depth analysis is made on refrigerators, ovens and range hoods. Legal requirements of the EU summarized and reviewed as well. New developments especially concerning regulation of "special purpose lamps" will be taken up.

Introduction

For purpose of illumination of interior space and working areas of electrical household appliances lamps are widely used. Quite common are incandescent lamps. They have been designed for these special applications mainly. The most prominent ones are oven lamps which are exposed to hot ambient conditions and refrigerator lamps which must fulfill special safety requirements.

Replacement has taken place across Europe in the past years driven by innovations from lamp industry. Despite this revolutionary development where LEDs have nowadays become very attractive still incandescent lamps are used. Especially this will continue spare parts in the next years.

The innovations happened in the past years are due market trends which itself are also driven by regulatory requirements to some extent.

Household appliances are entirely affected by energy efficiency trends and measures. In further reducing the energy consumption all sources are taken into account, whichever they are small or even very small. Contributions from lamps are small in general. But they could have measurable effect. Range hoods are an exception, because here illumination of the working area contributes much in relation to the other main function of ventilation.

The question now is:

What are the market trends?

What is the impact on energy efficiency of domestic appliances?

Appliances

Lamps have different functions.

1. Lamps for illumination of the interior space of an appliance
2. Lamps for illumination of working areas
3. Illumination of control elements, status displays, intelligent indications (like hob areas), light design and ambient lights.

Lamps for illumination of the interior space of an appliance

Refrigerators, freezers and ovens are the most important representatives of this category. Others are washing machines, dryers, microwave ovens etc.. A proper illumination of interior space allows users to operate the appliances in a good manner. Illumination increases the value of the appliances. Lamps are generating comfort. They are supporting users to operate appliances to avoid failures and increase safety as well.

Customers have different expectations. Lamps are product features and can create added value. But for various categories (e.g. refrigerators, ovens) lamps are a real obligation. However, the brightness of a lamp is remaining a marketing feature. Some refrigerators do have two lamps.

There are special requirements for the lamps. This is due to the special conditions in the interior of the appliance. Lamps for ovens are very special as they must endure high temperature. This is 300 or 400°C.

For refrigerators there are safety (i.e. temperature) requirements to be fulfilled. This is because of possible fire hazards in plastic material surroundings and the fact that the lamps should not heat up the cooling space by their own heat dissipation.

Design requirements are to be fulfilled for other appliances like washing machines and dryers because of temperature, shock, humidity etc..

Normally there is no special switch for the lamps which must be operated by the user. Refrigerators lamps are switched on when opening the door and switched off when closing it. Usually oven lamps are on all the time when oven is operated.

Visual impaired persons need good illumination of the interior space of appliances. This is a very important point. A great variety of appliances are supporting these related requirements with high luminous lamps or even two lamps instead of one lamp only.

Lamps for illumination of working areas

Range hoods are the most prominent appliance of this category. Here lamps are an additional function of the appliance itself. The lamps are switched normally independently from the ventilator. Lamps are very often ordinary lamps and the illumination often is seen as additional room lighting. No special requirements must be fulfilled. This is mainly due to the fact that lamps are not or less exposed to extreme environmental conditions.

For hoods there is a minimum requirement on brightness set out in ecodesign Regulation, see below.

Besides of range hoods there are a lot of other appliances for which illumination of working areas is evidently important. There is an added value. Examples are espresso machines, coffee makers. But other products also like irons or vacuum cleaners. The lamps are controlled by timers or sensors. Often LEDs are used which are highly integrated into other components. Therefore it is normally not possible to replace or repair such a system without disassembling of it and a complete exchange of this subsystem and spare parts are available via manufacturer after sales service only.

Illumination of control elements and status display

Illumination of control elements and status display is quite common. This makes the use of the appliance more convenient and foster safe operation. Especially for handicapped people (e.g. visual impaired persons) these features are essential. Quite often LED technique is used. The LEDs are normally integrated in the electronic components. Normally the electronic component will be replaced completely when it is broken down. However, LEDs have long lifetime and therefore the necessity of a replacement is very unlikely.

Replacement of incandescent lamps

From an engineering point of view replacement of incandescent lamps by fluorescent, halogen or LED lamps cannot be done without special care. Care is even necessary when replacing an incandescent lamp by another incandescent lamp. This is because of certain requirements related to safety, ambient conditions, quality, allowed heat dissipation, etc.. Spare part management is an additional point which even could be the most problematic one.

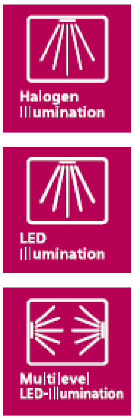
There is no data available at the moment on how many replacements have been realized and from which a forecast could be made for future exchanges for existing products. A common life time approach is not possible due to the special demands and usages of the appliances and the lamps.

However, BSH Hausgeräte GmbH, the largest household appliance manufacturer of Europe states that nowadays almost all refrigerator models marketed in Europe are equipped with LEDs since a couple of years. Although varying a little bit from country it is said that more than 90 % of its models are equipped with LEDs.

As concerning range hoods there are incandescent lamps, halogen lamps, LEDs and some fluorescent lamps is use for the new models. For the majority is in LEDs (approx. 75 %). This can be seen as a positive effect of the new label scheme and the ecodesign measures. LED is to be expected to take over and replace all other lighting technologies soon as the flexibility in solutions increase and the costs decrease in the same way.

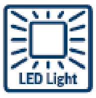
For ovens there is less replacement done so far only because of the non-availability of suitable alternatives. There are some models equipped with halogen lamps and starting also with LEDs.

According to the lighting industry this trend towards LED will continue. LEDs will become more and more common for various applications.



Everything put in a good light.

Depending on the model, there are different kinds of illumination inside the oven. Whether it's the standard Halogen light, LEDs or the most advanced Multilevel LED strip, they all provide a brilliant view of your dishes without having to open the oven door.



LED Light

Brilliant, even light to help you see inside the whole fridge interior more clearly, ensuring that you use your fridge space as efficiently as possible. Elegantly integrated into the top, or side of the fridge compartment, the light is unlikely to be blocked by food, giving you constant illumination every time you open the fridge door.

Figure 1. Advertisements, (see [1]). Oven (top), Refrigerator (middle and bottom)

Energy Consumptions

In this chapter some estimation on energy is made. Table 1 gives a summary.

Oven

Oven lamps are special lamps because of temperature conditions. Incandescent and halogen lamps with power consumptions of either 15 or 25 W are used. It is assumed a typical time of operation of 200 h / year (see also [12]). Hence annual power consumption is approximately 5 kWh / year. This is small compared to the overall power consumption of an oven (less than 1%). Nowadays there are LEDs used. Power consumption is in the range of some Watt.

Oven lamp does not waste energy. The lamp is generating heat which is useful energy for the main function of the oven itself, i.e. baking. Moreover it is quite common to use the oven for making yoghurt by simply using the lamp as a heating element.

Refrigerator

Incandescent lamps are used since many years. Halogen lamps are very rare. Since some years there is a clear trend towards LEDs. Some manufactures have replaced its assortments to great extends.

Fluorescent lamps are disadvantageous for refrigerators (as they need time for being full effective and do not be effective in cold surrounding). Thus fluorescent lamps have almost never been used.

From Figure 1 it is quite obvious that light is a marketing issue. The trend towards LEDs is driven by energy efficiency. However there are ergonomic reasons and durability aspects also.

For our energy calculation a 50 h per year duration is assumed (i.e. opening of the door), see also [12]. The energy consumption is small, see Table 1.

It is to be noted that the effect of heating effect makes the energy consumption twofold (more or less).

Range hoods

Range hoods manufacturers are using a great variety of lamp technologies. Almost every technology is applied, see Table 1. For the energy calculation an average time duration of 2 h per day is assumed (see also [12]), as this is assumed to be a representative figure in the context of the EU Regulation on labeling (see [8]). The contribution is quite big for incandescent lamps and of the same magnitude to the energy consumption of the ventilation system. Ranges hoods equipped with LEDs are capable to enter into class A or better only and improve the energy efficiency class of the appliance in an elegant way. Thus the market picked up the new lamp technologies very quick and this can be seen as a very successful example for market changes driven by the right incentive structure. For more details see section below.

Other products

Some washing machines, dryers and coffee machines etc. are equipped with lamps as well. This creates value. Ergonomics and aesthetic aspects are the driving forces behind. It must be considered that for washing machines and dryers the energy consumption of the lamps is fully integrated into the overall energy consumption which relevant for the calculation of the annual consumption and energy efficiency class. See Table 1.

EU Regulation on standby power consumption is to be considered. Thus working areas of coffee and espresso machines are illuminated for a short time interval only.

Control elements and status display

This paper is dealing with lamps. But for sake of completeness authors mention controls and status displays also. The energy consumption is negligible in general. Table 1 is showing a typical configuration. In exceptional cases there could be higher power consumptions present (up to max. 2 W, according to the authors). These illuminations are normally switched off or reduced automatically after user interferences.

Table 1: Indicative figures on energy consumed of lamps used in household appliances.

	Technology (typical power consumptions)	Indicative energy consumptions per year	Socket (typical)
Ovens	incandescent lamps (15 W, 40 W) halogen (15 W, 30 W) LED (2 W)	5 kWh 5 kWh 0,5 kWh (100 - 150 kWh [4])	E14 E14, G9 E14
Refrigerators and freezers [1]	incandescent and halogen lamps (15 W, 25 W, 40 W) and LEDs (0,3 W, …, 3 W)	1 kWh [2] 0,1 kWh (100 - 300 kWh [4])	E14, E27 E14, integrated [3]
Range hoods [1]	incandescent (25 W, 40 W) halogen lamp (20 W, 30 W) fluorescent (10 W) LED (4 W)	20 kWh 20 kWh 7 kWh 3 kWh (30 - 150 kWh [4])	E14, E27 E14, G4 E14 E14, G4, integrated [3]
Washing machine and dryers	Incandescent lamps (10 W) LEDs (2 W)	5 kWh 0,5 kWh (150 / 250- 500 kWh [4] for washing machines / dryers)	E14 E14, integrated [3]
Coffee and espresso machines	Incandescent lamps (2 W) LED (0,2 W, … 1 W)		integrated [3]
Control elements and status display	LED (0,2 W)	0,2 kWh	Integrated [3]

[1] Some appliances do have two lamps (or even more) for better illumination purposes.
[2] 3 kWh, for 60 W lamps.
[3] "integrated" means: LEDs are assembled directly on certain modules or units of the appliance.
[4] Typical annual energy consumption of appliance.

When compared to the total energy consumption on an appliances it can be stated that lamps consume approximately 1 %, except for range hoods, where the contribution of lamps is much higher.

This seems rather small and negligible (like standby for those products). However, because of the huge number of appliances the energy consumption is remarkable high. In a rough estimation savings of about 2 TWh could be achieved per year by 2030, assuming all lamps have been replaced by LEDs. Further information is provided by [12].

How does EU Regulations on lamps affect household appliances?

Ecodesign Requirements

Two EU Regulations on ecodesign do have impact on household appliances. These are Regulation on non-directional lamps, (EU) No 244/2009 (see [2]) and Regulation on directional lamps and LEDs, (EU) No 1194/2012 (see [3]).

Both Regulations set minimum requirements on energy for household lamps. Lamps integrated in household appliances are not affected as they are "special purpose lamps". The Regulation does not apply because these lamps are not used for room illumination purposes (see [5]).

Regulation on directional lamps and LEDs is setting information requirements. But there is no obligation concerning household appliances, except for spare parts. It must be made clear to the customer that spare parts are not going to be misused, i.e. used for room illumination. Therefore there must be a text at the packaging of such spare parts saying that such a lamp is "not suitable for household room illumination" according Annex I (see [3]). Alternatively a pictogram is used, see Figure 2. The meaning is simply, that the lamp is not suitable for household room illumination. The bulb which is framed by a house is crossed out. This pictogram is widely used for spare parts. However, it must be stated that till now there is no data available showing that the information requirements has any impact on consumer behavior.

Figure 2: Pictogram indicating not suitable room illumination (see [5]).

The purpose of special lamps is often explained on packages by means of schematic drawings. Figure 3 shows two examples from OSRAM spare parts. The drawing is explaining that the respective lamp is designed for a special purpose. The meaning is that these lamps withstand extreme temperature and shock conditions.

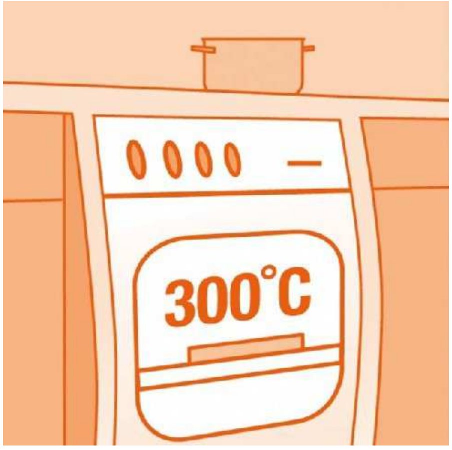


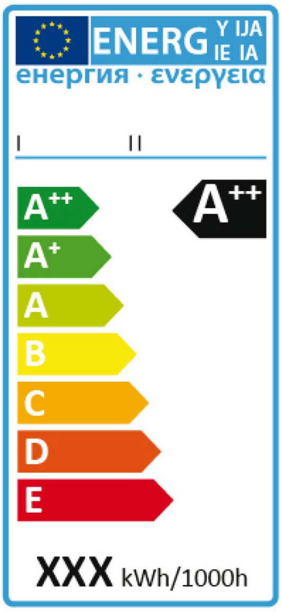
Figure 3: Pictograms printed on the packaging of lamps explaining the purpose of a special lamp. From package of OSRAM special refrigerator incandescent lamp T/Fridge, 15 W (above) and OSRAM special oven incandescent lamp CL15, 15 W (below).

The point “special purpose” lamp is presently under discussion. It has been turned out from “review study on stage 6” (see [6]) and “omnibus review study” (see [7]) that there is a loophole on both regulations on non-directional and directional/LED lamps (see [2] an [3]). There is a misuse of the so called “special purpose lamps” (respectively “special purpose products”). These lamps are very diverse and lamps integrated into household appliances are covered also. Free riders make use of this definition and place on the market lamps by using this loophole in order to define existing lamp solutions (like incandescent lamps) to be “special purpose” ones and being needed as replacement solutions for existing appliances in the market . But they are still ordinary lamps. Shock proof lamps which are used for many applications might be the most prominent ones (see [6]). There is no evidence so far that there is any misuse of lamps from household appliances. Nevertheless EU Commission intends to cover all area where special purpose lamps are used. Industry is worried about draft regulatory text from EU Commission (see [7]) as it is obliged that special purpose lamps shall be always in the highest energy labeling class. This could not be implemented on practical considerations and is not compatible with the principle of least life cycle cost which is set out in the Framework Directive (see [9]). A solution could be setting limits on energy consumption 25 W and / or a size 60 mm. Additionally it could be broadly discussed whether and in what appliances need special purpose lamps followed by dedicated permissions for applicants, that want to place on the market these special purpose lamps. Besides these limits the lamps should be not called “special purpose lamps” and hence must fulfill the “normal” requirements on energy consumption.

A review study concerning all lamp Regulations in place [2], [3], [4] was started in 2014. This is led by VHK [12]. This study will be the base for revision of the legislative measures.

Labeling Scheme

EU Regulation on labeling of lamps was revised in 2012. The new Regulation (EU) No 874/2012 goes beyond this old labeling scheme as new innovative lamp technologies and luminaries are covered now (see [4]). But lamps in household appliances are excluded because the “primary purpose is not lighting” (Art. 1(e), see [4]). But for spare parts the label must be applied. This should allow customers to make a buying decision based on energy considerations.



or

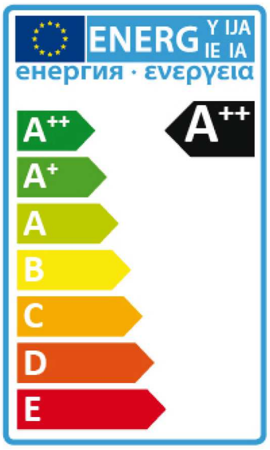


Figure 4: Energy label layout, (see [3]).

This requirement on spare parts is still been challenged because a labeling system makes no sense if there is no real possibility for making alternative buying decisions.

Range hoods

In 2014 the two EU Regulations on labelling (see [10]) and ecodesign (see [11]) on range hoods have been published. Besides the main function, i.e. ventilation, these regulations are setting requirements on lamps also. Since January 1, 2015 the label is mandatory in EU. And since February 20, 2015 minimum requirements have to be fulfilled.

The label includes the lighting efficiency class (see Figure 5). Moreover the fiche includes additionally lighting efficiency in lux/Watt under standard conditions to be declared. It is important to know that this lighting efficiency class is defined according to the needs of the appliance to illuminate the hob space area and is not identical to the efficiency class of the used lamps.

The ecodesign measures set out a minimum requirement for the total energy consumption (which is including the energy consumption of the lamps). Furthermore it requires minimum illumination performance of a cooking surface. This is 40 lux under standard conditions.

It can be summarized, that these EU Regulations are going far beyond the “normal” Regulations of household lamps (see [2] and [3]) as they integrate lighting efficiency and concrete illumination requirements.

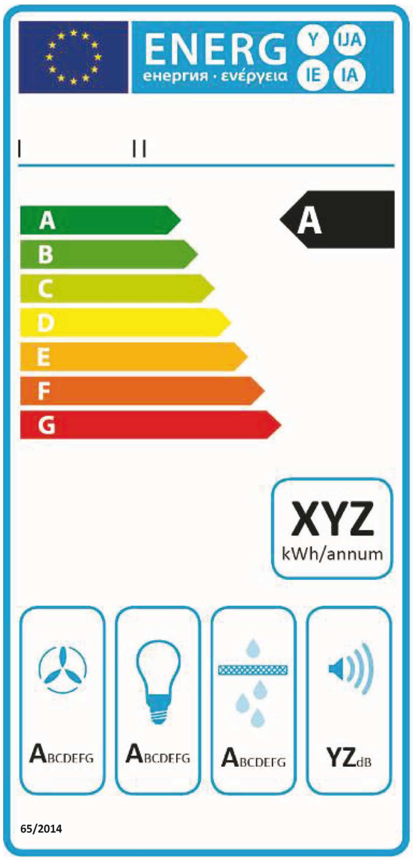


Figure 5: Energy label layout for range hoods.

Conclusion

There is progress towards less energy consuming lamps. The trend will continue. The main drivers are innovations made by lamp industry for better energy efficiency and durability. But ergonomic and aesthetic aspects are drivers as well.

Regulatory measures are in place already. Further measures are not really necessary and could have even negative effects, as the progress is driven meanwhile vividly by competition and demand for low energy consuming solutions by manufacturers and consumers.

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Potential for improving energy efficiency of built-in refrigerators

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Abstract

In the present study, experimental and computational investigations were carried out to investigate and optimise installation conditions that have significant effects on the energy efficiency of built-in refrigerators. Investigated parameters include the condenser's position in relation to the adjacent surfaces, the diameter of air vents at the top and the socket of the cabinet, the gap between the refrigerator's back wall and the rear wall of the cabinet, air flow velocity and materials of the cabinet. In particular, the focus here is on accelerating heat removal from the condenser and, by implication, on reducing the condenser's temperature, which is the most crucial factor for refrigerators' energy consumption. Experiments were carried out with a built-in refrigerator and validated using a built-in fridge-freezer combination. The results of both, experimental and numerical approaches will be presented.

Introduction

In 2010, the final total electricity consumption in European households (EU-27) was about 2836.6 TWh [1]. A substantial share of 14.5 % of this electricity is consumed by refrigerators and freezers, corresponding to 411 TWh. Domestic refrigerators and freezers prove to be different from other appliances, since they are the only devices in private homes which are permanently connected to the power supply and which are common in nearly every household in developed countries. This is the reason why great efforts have been made to reduce their energy consumption. As a result of the implementation of the European Energy Label, new technical developments and improvements could be achieved and the energy consumption has decreased by about 60 % [2]. These reductions are mainly traceable to more efficient and lower dimensioned compressors as well as to improved insulations (for example vacuum panels).

In view of built-in refrigerators and freezers, energy efficiency could not be enhanced in the same way and these appliances consequently are seldom graded into the highest energy efficiency classes despite their high market share in Europe and many other parts of the world. Standardised niche measures for built-in appliances might be seen as the main reason for the lower efficiency. In the case of built-in appliances, insulation is limited to a certain extent as additional insulation material would decrease refrigerator's net volume. [2] In view of stand-alone appliances, the size constraints are much less strict than in the case of built-in appliances meaning that deficits in volume can be compensated more easily. The thickness of the layer of insulation is directly related to the heat load by conduction through cabinet walls, which accounts for 60-70 % of refrigerators' heat load [3]. Moreover, energy consumption of a built-in appliance does not only depend on its technical components, but rather the way it is installed in private kitchens has a decisive influence. Simple calculations suggest that even minor modifications of air vents may have a significant impact on the ventilation of the appliances. Accordingly, an insufficient air vent will cause heat, which is emitted by the condenser coils on the back wall of the refrigerator, to accumulate inside the refrigerator cabinet. Consequently, conduction through the refrigerator walls will increase and will lead to an increase in energy consumption. On the other hand, oversized air vents waste space, which otherwise could be used for additional insulation.

Up to now, only a few studies have been conducted on this topic. An experimental study on the performance of wire and tube condensers as a function of its geometry and its position to the adjacent (back, side and bottom) walls was carried out by Melo *et al.* in 2004 [4]. The main components of this condenser are a steel tube, which is bent into a snake like shape, and wires, which are vertically attached on both sides of the tube [5]. This kind of condensers is common for household refrigerators and freezers worldwide. For reasons of simplicity, the refrigerator in this study was represented by a special experimental apparatus, consisting of hot water circulating through a heat exchanger. The main findings of this study are as follows: the gap between the refrigerator and the rear wall has a decisive influence on the performance of wire and tube condensers. There is an optimal gap between the refrigerator and the rear wall, where the heat transfer rate is maximal. Modifications in both directions, decreasing and increasing gap, lower heat transfer rate because of a reduction in buoyancy. The optimal position of the condenser is half the distance between the refrigerator and the rear wall.

To the best of our knowledge, no further studies were published on optimizing the interaction between refrigerators and the cabinets they are built-in. The objective of the present study is to investigate whether and to what extent the energy consumption of built-in refrigerators and freezers can be reduced by modifying installation conditions (e.g. air vents, gap between refrigerator and rear wall or side walls, air flow velocity). The main focus is on accelerating heat removal from the condenser and on reducing the condenser's temperature, which is the most crucial factor for refrigerators' energy consumption [6, 7].

Material and methods

Experimental as well as numerical (Computational Fluid Dynamics CFD) approaches are applied in this study.

Numerical approach

Computational Fluid Dynamics (CFD) is a simulation method widely used in engineering to analyse and predict heat transfer and fluid flow by numerically solving the Navier–Stokes equations. In order to enable a comparison of experimental data and numerical results, the geometry of the test appliance and the test cabinet was simulated in accordance to installation instructions and meshed into discrete cells. To improve the prediction of heat transfers, a high-resolution mesh was used locally. The cooling fins of the condenser were simulated as a condenser plate as shown in Figure 1 in order to avoid a too complex geometry.

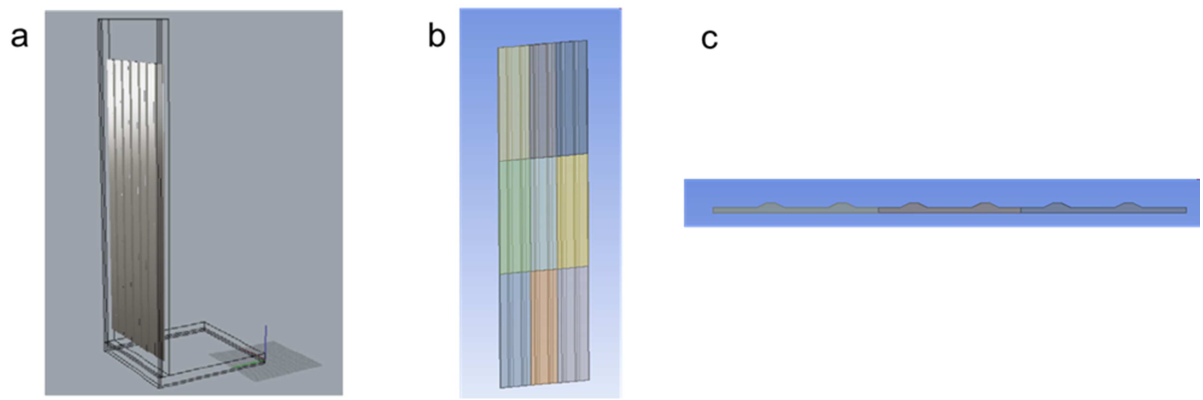

Figure 1: Geometry of condenser, (a) geometry model, (b) front view, (c) top view (source: Transsolar Energietechnik GmbH)

Depending on the power class of the refrigerator (60 W, 90 W and 120 W), a respective maximal thermal performance (150 W, 225 W and 300 W) was equally imprinted on the condenser. For simulation, the following assumptions were made:

- Walls are adiabatic meaning that heat is exclusively supplied and dissipated by the wires and tube of the condenser and the air vents
- On the side walls, air gap is closed adiabatically
- External temperature is constant (21 °C)

SIMPLE–Algorithm (Semi-Implicit Method for Pressure Linked Equations) was applied to solve the Navier-Stokes- Equation. For turbulence modeling, the RANS (Reynolds Averaged Navier Stokes)-k-ε-model was used. CFD simulations were carried out by the climate engineering firm Transsolar (Stuttgart, Germany), whereas the CFD software programmes Fluent and Workbench 14.5 (ANSYS Inc.) were used to perform the simulations.

All in all, three references (measures recommended by manufacturer) corresponding to three power classes and seven variants were simulated:

Reference 90: This variant reflects the test refrigerator and the recommended installation measures of the experimental part of the project. The power class of the device is 90 W (thermal performance of condenser = 225 W), the distance between the refrigerator back wall and the condenser is 10 mm. The gap between the refrigerator and the rear wall is assumed to be 50 mm. According to the installation recommendations, air vents at the inlet (socket) and the outlet (top) are 200 cm^2, respectively.

Reference 60: With the exception of the power class (60 W, thermal performance of condenser 150 W), this variant is identical with “Reference 90”.

Reference 120: Except for the power class (120 W, thermal performance of condenser 300 W), this variant is identical with “Reference 90”.

Variant 1: This variant is almost identical with “Reference 90”. As a difference, the rear wall is simulated as a copper sheet (non-adiabatic, thickness 2 mm), whereas the ambient temperature is assumed to be 20 °C.

Variant 2: This variant is almost identical with “Reference 90”. As a difference, the gap between refrigerator’s back wall and the rear wall is decreased by 20 mm (from 50 mm to 30 mm) and the condenser is fixed half the distance between the refrigerator back wall and the rear wall.

Variant 3: The variant corresponds to “Reference 90”. In this variant, air velocity inside the rear gap is doubled (0.8 $m \cdot s^{-1}$) compared to natural convection.

Variant 4: This variant corresponds to “Reference 60”. However, the condenser is located half the distance between the refrigerator back wall and the rear wall.

Variant 5: In this variant, air velocity inside the rear gap is doubled (0.8 $m \cdot s^{-1}$) compared to natural convection. The variant is based on “Reference 60”.

Variant 6: It also assumes the condenser to be located half the distance between the refrigerator back wall and the rear wall. This variant is based on “Reference 120”.

Variant 7: In this variant, air velocity inside the rear gap is doubled (0.8 $m \cdot s^{-1}$) compared to natural convection. The variant corresponds to “Reference 120”.

Table 1 gives an overview of all variants.

Table 1: Variants of simulation

	Reference			**Variant**						
	90	**60**	**120**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Power class (W)	90 W	60 W	120 W	90 W	90 W	90 W	60 W	60 W	120 W	120 W
Distance refrigerator back wall-condenser	10 mm	10 mm	10 mm	10 mm	15 mm	10 mm	25 mm	10 mm	25 mm	10 mm
Air vents (inlet/ outlet)	200 cm^2	200 cm^2	200 cm^2	200 cm^2	200 cm2	200 cm2	200 cm^2	200 cm^2	200 cm^2	200 cm^2
Gap refrigerator-rear wall	50 mm	50 mm	50 mm	50 mm	30 mm	50 mm	50 mm	50 mm	50 mm	50 mm
Forced ventilation	-	-	-	-	-	0.8 $m \cdot s^{-1}$	-	0.8 $m \cdot s^{-1}$	-	0.8 $m \cdot s^{-1}$
Material of rear wall	wood			cop-per	wood					

Variants are compared and evaluated based on the average condenser's temperature, which correlates well with the mass flow and which is the most crucial factor for refrigerators' energy consumption.

Experimental approach

In order to validate the numerical results, experiments were carried out with a commercially available built-in refrigerator. The appliance with an indicated power class of 90 W is rated in energy efficiency class A^{+}. The refrigerator is dynamically cooled with a net volume of 0.308 m^3. It is equipped with a wire and tube condenser, which is fixed at a distance of 10 mm from refrigerator's back wall.
The refrigerator is installed into a test enclosure made of dull black painted plywood (thickness 20 mm). This test enclosure was specially designed and built for the purpose of this study. It offers a high flexibility in varying the position of the side walls and the rear wall as well as the area of the air vents. In order to enhance ventilation inside the cabinet, two PC cooling fans (diameter: 12 cm, speed of rotation: 2000 rpm, free air delivery: 126 m^3/h) can be additionally integrated into the socket. Figure 2 shows schematic diagrams of the test enclosure.

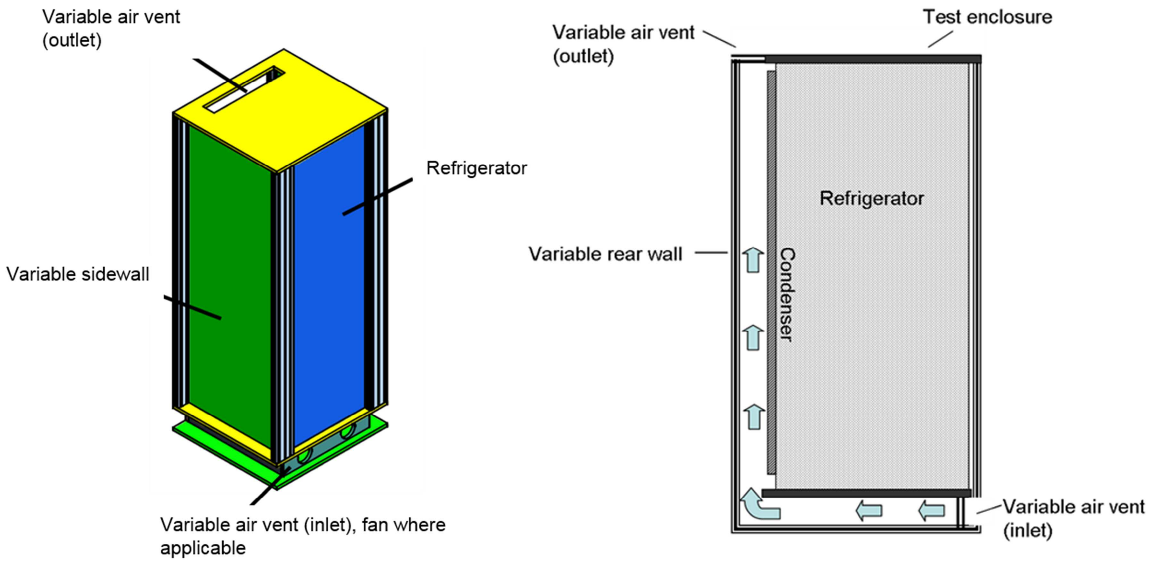

Figure 2: Schematic diagrams of the test enclosure showing variable components and airflow along the condenser (source: own illustration)

All experiments were carried out in a climatically controlled chamber at an ambient temperature of 21 °C, the internal fridge temperature was adjusted at 5 °C.

Energy consumption tests were largely conducted following the European standard for household refrigerating appliances. Experimental data like internal compartment temperatures (°C), ambient temperature (°C), ambient humidity (% RH), refrigerator's energy consumption (Wh), power (W), voltage (V) and current (A) were recorded using a computer-based data-acquisition system. All data were recorded at 60-second intervals for at least 24 h. Compartment temperatures were measured in accordance with the European standard using three type T (copper-constantan) thermocouples with a measurement uncertainty of ± 0.2 °C inserted in a brass cylinder. The air velocity and air temperature inside the flow passage near the inlet and outlet of the air was measured using two thermoanemometers (measuring range: 0.08-2.00 m/s, accuracy: ±(0.04 m/s + 1 % of measured value)). Both were fixed inside the enclosure, one near the air inlet at the plinth, the other near the outlet of the air at the top. Temperatures of the condenser coils were measured by nine thermocouples type T equally distributed along the height and width of the condenser.

To study the effect of different wall positions and areas of air vents, a reference point was used which corresponds to the measures recommended by the manufacturer (gap between refrigerator and side walls: 11 mm, gap between condenser and rear wall: 50 mm, area of air vents: 200 cm^2).

Results and discussion

With regard to variant 1, the numerical simulations have shown that condenser's temperature is reduced by 2.2 % compared to "Reference 90". Additionally, air temperature at the outlet as well as mass flow are reduced in comparison to the reference variant meaning that only 60 % of heat emitted by the condenser is dissipated via natural convection through the air gap and 40 % is dissipated by the copper sheet.

In the case of variant 2, the gap between refrigerator's back wall and the rear wall was decreased by 20 mm (from 50 mm to 30 mm) and the condenser was assumed to be half the distance between the refrigerator back wall and the rear wall. Numerical results have shown that condenser's temperature is virtually not influenced by this measure and remains at the same level as in the case with the corresponding reference. However, temperature gradient between the lower and the upper part of the condenser is considerably higher than for the reference variant. Due to a reduction in rear gap, cross-sectional area of the air vents is also reduced compared to the reference resulting in a lower mass flow and a higher air temperature at the outlet.

If the air velocity is doubled compared to natural convection (variant 3), simulations suggest a reduction of condenser's temperature by 17 % compared to the corresponding reference.

Figure 3 summarizes the results mentioned above.

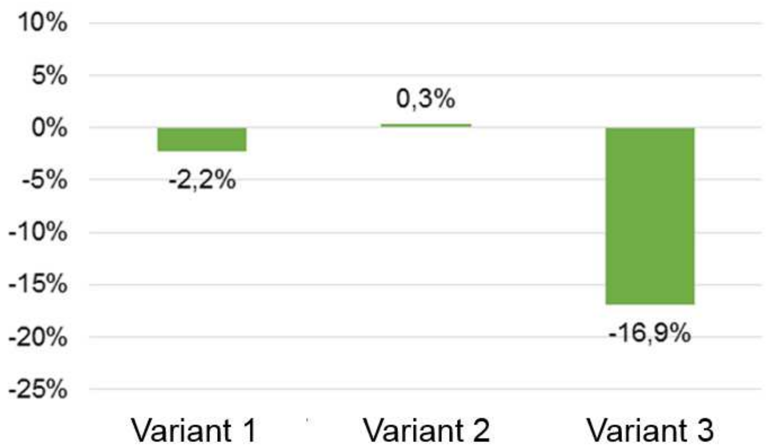

Figure 3: Changes in average temperature of condenser in comparison to „Reference 90" (source Transsolar Energietechnik GmbH)

In accordance to the results of [4], CFD simulations (variant 4) have revealed that condenser's temperature is reduced by 8 % if the condenser is fixed half the distance between the back wall of the refrigerator and the rear wall (Figure 4). If the condenser is positioned at exactly half the distance between both adjacent surfaces, heat transfer takes place equally on both sides of the condenser, which results in an improved heat transfer.

As shown in Figure 4, average condenser's temperature is lowered by about 20 % if air velocity inside the rear gap is doubled (0.8 $m \cdot s^{-1}$) by mechanical ventilation (variant 5).

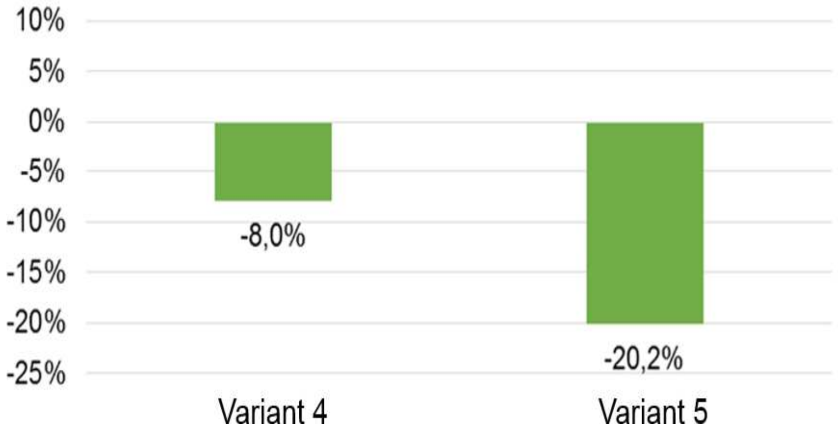

Figure 4: Changes in average temperature of condenser in comparison to „Reference 60“ (source Transsolar Energietechnik GmbH)

Changes in average condenser’s temperature in comparison to “Reference 120” are shown in Figure 5.

If the condenser is positioned half the distance between the refrigerator and the rear wall, the average condenser’s temperature is lowered by about 8.1 % compared to the corresponding reference (variant 6).

An even higher reduction in condenser’s temperature (15.2 %) is obtained with regard to variant 7 by doubling air velocity inside the rear gap (0.8 $m \cdot s^{-1}$).

Figure 5: Changes in average temperature of condenser in comparison to „Reference 120“ (source Transsolar Energietechnik GmbH)

Most of the aforementioned results could be confirmed by experimental investigations.

Figure 6 illustrates changes in energy consumption as a function of the gap between the refrigerator and the rear wall of the enclosure. It can be noted that energy consumption decreases with increasing gap between refrigerator and rear wall, which is mainly caused by an increase in circulating air flow. The highest energy consumption is measured at 10 mm (516.2 Wh). A minimum of 362.1 Wh is reached at 30 mm. Between 30 and 110 mm, energy consumption remains constant. Regarding condenser’s temperatures and air velocities inside the rear gap, a reduction in temperature on the one hand and in buoyancy on the other hand can be observed with an increasing gap. In summary, the results are in accordance to the results of the numerical simulations (variant 2) and suggest that the gap between refrigerator and rear wall can be reduced by 20 mm compared to actual recommendations (50 mm) without negative effects for energy consumption.

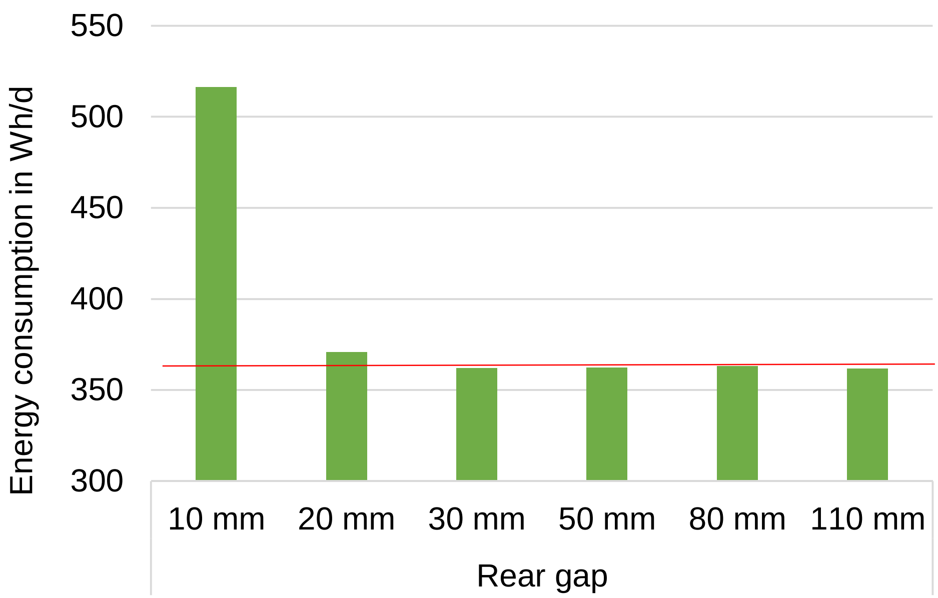

Figure 6: Experimental results showing changes in energy consumption with modifications in rear gap compared to reference (rear gap: 50 mm)

As a consequence, the insulation layer of the refrigerator may be extended by 20 mm using this additional space, in spite of standardised kitchen cabinet dimensions.

By doubling air velocity inside the gap, condenser's temperature could be reduced by 15 K compared to the reference. Together with this, energy consumption could be lowered by 7-12 % (absolute savings 25-40 Wh per day), whereas the savings increased with decreasing rear gaps. However, additional power is needed to operate a mechanical ventilation system. In order to calculate net efficiency improvements, this additional power has to be taken into account.

In accordance to the numerical results (variant 4 and 6), experimental results have sown that the optimal position of the condenser is half the distance between the back wall of the refrigerator and the rear wall. In this way, heat transfer was improved, mass flow was increased and condenser's temperature was lowered resulting in energy savings of about 6 %.

With regard to variant 1, CFD simulations revealed that condenser's temperature is reduced by 2.2 % if the rear wall is simulated as a copper sheet. This result could not be confirmed in experimental investigations.

Experimental results further suggest that there is a positive correlation between the energy consumption and the gap between the refrigerator and the side walls of the cabinet: the smaller the gap, the lower the energy consumption. A lateral gap of 20 mm causes an additional consumption of about 2-3 % compared to the reference variant (gap 1 mm). This is because heat, which is emitted by the condenser, is enabled to enter the compartment by conduction through the side walls of the refrigerator. If the lateral gap gets smaller, heat exchange is reduced. Regarding the reference variant, side walls may be considered as virtually adiabatic.

The results were validated using a built-in fridge-freezer.

Conclusion

The results have shown that the airflow inside the air gap as well as the energy consumption of built-in refrigerators are highly sensitive to installation conditions. As a consequence, there is a high potential for reducing energy consumption of built-in refrigerators by modifying these conditions.
The gap between the rear wall and the refrigerator has the highest impact on heat dissipation and, related with this, on energy consumption. Experimental and numerical results portend potential improvements of energy efficiency if the gap is reduced by 20 mm compared to actual recommendations and if the cabinet is enlarged to the same extent. The additional space may be used

for extending refrigerator's insulation layer or as additional net volume. In both cases, energy efficiency will increase.

CFD simulations and experiments revealed that the optimal position of the condenser is half the distance between the refrigerator and the rear wall.

In view of the numerical and experimental findings, it seems to be promising to enhance air velocity inside the rear gap by mechanical ventilation. However, additional power is needed to operate a mechanical ventilation system, which has to be taken into account. Here, further experiments are needed.

Even though CFD simulations portend potential efficiency improvements by changing material of the rear wall (copper sheet because of increased thermal conductivity), this trend could not be confirmed in experimental investigations.

Experimental results suggest that the gap between the refrigerator and the side walls should be small to avoid heat exchange with the side walls of the refrigerator.

In this study, the refrigerator was installed into a test enclosure as described above. The enclosure was freestanding and not part of a kitchen unit. In real life, however, the cabinet is often located just nearby an external heat source (e.g. oven or dishwasher) or exposed to direct sunlight. In this respect, future work has to show whether there are significant influences on heat removal. Moreover, the applicability of the results to other refrigerators and freezers has to be tested in further studies.

Acknowledgement

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Cold wash – Tests on the washing performance

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Abstract

Heating-up cold tap water to 30°C, 40°C, 60°C or even 90°C uses the lion's share of washing machines' electricity consumption. «Cold wash» – washing at 15/20°C – saves about 60% electricity compared to a cycle at 40°C. In the EU-27 «cold wash» can save up to 11 TWh per year, which equals 2'200 million Euros or the annual production of the nuclear power plant Emsland.

The EU Ecodesign Regulation requires washing machines to offer a washing cycle at 20°C and a variety of detergent designed for these temperatures are available in Europe. Despite all of this, prejudices and habits prevent most consumers from «cold wash».

Discussions on «cold wash» – especially on the washing performance – run often controversial and emotional. To contribute to the debate with impartial and scientific facts, Topten arranged 24 test situations to measure and compare the washing performance and energy consumption at 40°C and 20°C. Hereby factors influencing the washing result were systematically investigated such as detergent, pre-treatment of stains, washing machines and loading. The tests were carried out in collaboration with the VDE Testing and Certification Institute and with the support of the Elektrizitätswerke des Kantons Zürich and Stiftung Warentest in December 2014.

Good washing performance at 20°C is reached when using a good machine and good detergent. It is assumed that «cold wash» absolutely is appropriate for lightly and normally soiled laundry and that it is worthwhile to encourage consumers to try it out.

The paper concludes with recommendations for various stakeholders such as EU policy makers, manufacturers and retailers, NGOs and academia.

Introduction

The washing of clothes and textiles is part of our everyday routine, but by using energy and water it puts a strain on our environment.

«Cold wash» – washing at 15/20°C – holds a tremendous energy and CO_2 saving potential, as the lion's share of washing machines' electricity consumption is used for heating-up cold tap water to 30°C, 40°C, 60°C or even 90°C.

At EEDAL 2013 Topten presented the paper «Cold Wash – Do Prejudices Impede High Energy Savings?» [1]. It showed that washing machines with a 15/20°C-cycle and appropriate detergent active at these low washing temperatures both are available on the European market. It showed also that in the case a consumer perceives the washing result as insufficient, it is not necessarily the fault of the «cold wash», but may have a number of other causes such as laundry sorting, pre-treatment of stains, loading of the washing machine etc. It was concluded that it is mainly prejudices, but also tradition and custom, that hinder consumers from taking the step towards «cold wash».

According to the Sinner circle the washing performance always depends on the interaction of the four factors temperature, chemistry (e.g. detergent, pre-treating of stains), mechanics (e.g. the agitation of the laundry in the drum) and time. All four factors are interdependent, but inter-changeable in size. If one of the factors is changed, it must be compensated with one or more other factors in order to achieve the same satisfactory washing result.

It is noted repeatedly that discussions on «cold wash» – especially on its washing performance – often run emotional and controversial. To contribute to the debate with impartial and scientific facts, Topten [2] arranged 24 test situations to compare the washing performance at 40°C and at 20°C. Thereby factors influencing the washing performance were systematically investigated at both temperatures such as detergent (three products), pre-treatment of stains (yes and no), washing machines (three models) and loading (half-load and full-load). The measurements followed EN 60456. To the knowledge of the authors, this test arrangement is a novel approach. During the wash cycles also electricity consumption and programme time were recorded. The tests were carried out in December 2014 in collaboration with the VDE Testing and Certification Institute [3] and with the support of the Elektrizitätswerke des Kantons Zürich EKZ [4] and Stiftung Warentest [5].

Hygiene was not part of the tests, although an often noted concern and given argument against «cold wash». The rationale is that hygiene is a complex topic for itself, which should not be correlated only with temperature. One has to be aware that bacteria multiply most rapidly at warm temperatures and not as often feared at 20°C and that it is more relevant how well they get washed out. A research of the University of Bonn and Hochschule Rhein-Waal showed that energy saving washing programmes remove due to their long programme time many germs from the laundry even at low temperatures. Bleach can help hereby. Those bacteria and fungi surviving at low temperatures even with bleach are assumed to be no danger for healthy people [6]. However, it is recommended to frequently wash the laundry at 60°C for persons having a weak immune system, a contagious disease or an allergy on house dust mites [7].

Biofilm was also not part of the tests. This film of bacteria and fungi multiplies in the humid environment of the washing machine and likes to settle especially on plastic parts, hard to reach areas and on the washing machine's drum. However, it can be avoided with simple measures such as taking the laundry as soon as possible out of the machine after washing, leaving the door of the washing machine and of the detergent compartment open so that the residual moisture can evaporate and running a load of laundry at 60°C with heavy-duty detergent occasionally [6], [7].

This paper first describes the methods and test conditions. Then it presents and discusses the results and concludes with recommendations for various stakeholders such as EU policy makers, manufacturers and retailers, NGOs and academia.

Methods and test conditions

The measurements followed EN 60456 [8] with the accordingly test laundry existing of cotton towels, pillowcases and sheets, with the accordingly test strips soiled with the five standardized stains sebum/pigment, mineral oil/black carbon, blood, chocolate/milk and red wine, with the accordingly number of laundry pieces for the loadings «half» and «full» etc. The measurements were carried out under normative test conditions. Details are described in the test report [9].

24 situations were arranged (each 12 at 40°C and at 20°C) to investigate the influence on the washing performance by detergent, pre-treatment of stains, washing machine and loading (Table 1). As some situations could be used multiple times[1] in total 18 tests were carried out (each 9 at 40°C and at 20°C).

[1] Situation S1 is the same as S5; Situation S2 is the same as S8 and S11.

Table 1 Overview on the test arrangement

	Fix	Varying	Temp.	Test		Situation
Influence of detergent	no stain remover good machine half-load	good detergent	40°C	Test 2a	T2	S1
			20°C	Test 2a		
		medium detergent	40°C	Test 3a	T3	S2
			20°C	Test 3b		
		sufficient detergent	40°C	Test 5a	T5	S3
			20°C	Test 5b		
Influence of pre-treatment of stains	good detergent good machine half-load	plus stain remover	40°C	Test 1a	T1	S4
		plus stain remover	20°C	Test 1b		
		no stain remover	40°C	Test 2a	T2	S5
		no stain remover	20°C	Test 2b		
	sufficient detergent sufficient machine half-load	plus stain remover	40°C	Test 8a	T8	S6
			20°C	Test 8b		
		no stain remover	40°C	Test 9a	T9	S7
			20°C	Test 9a		
Influence of washing machine	no stain remover medium detergent half-load	good machine	40°C	Test 3a	T3	S8
			20°C	Test 3b		
		medium machine	40°C	Test 6a	T6	S9
			20°C	Test 6b		
		sufficient machine	40°C	Test 7a	T7	S10
			20°C	Test 7b		
Influence of loading	no stain remover medium detergent good machine	half-load	40°C	Test 3a	T3	S11
			20°C	Test 3b		
		full-load	40°C	Test 4a	T4	S12
			20°C	Test 4b		

Products were selected as followed:

- Detergent: For the tests three detergent were used – a good, medium and sufficient one. The «good» and the «sufficient» detergent were selected with regard to their washing performance according to test results published by Stiftung Warentest [10]. The «medium» detergent corresponded to the standard-detergent «IEC A*» according to EN 60456 [8]. All three detergent were heavy-duty powders with bleach.

- Stain remover: The stain remover was selected on an expert's recommendation and is assumed to be a wide spread product on the European market.

- Washing machines: For the tests three washing machines were used – a good, medium and sufficient one. All washing machines were selected with regard to their washing performance according to test results published by Stiftung Warentest [6]. They are of different brands, but do all have the same rated capacity, are all rated in the best Energy efficiency class A+++ according to the EU Energy Label [11] and fulfil the EU Ecodesign requirements regarding the washing performance [12].[2]

Test-programmes were the 40°C-standard cotton programme and the 20°C-programme.

- The tested 40°C-standard cotton programme corresponds to the one which is also tested and used for the EU Energy Label [11] and the EU Ecodesign Regulation [12] to calculate the Energy Efficiency Index, water consumption, remaining moisture content and Washing Efficiency Index.
- The tested 20°C-programme is the one, which is mandatory according to the generic Ecodesign requirements since end 2013 [12][3].

With the exception of the tests at full-load (T4a and T4b) it always was tested at half-load[4]. Rationales are: The 40°C-standard cotton programme at half-load is part of the tests needed to calculate the Washing Efficiency Index in accordance with the Ecodesign Regulation [12]. Furthermore half-load better reflects real consumer behaviour: average washing-load in European households is assumed to be between 3 and 4 kg [1].

During the wash cycle electrical energy consumption and programme time were recorded. Also recorded but in this paper not considered were water consumption, amount of alkalinity remaining in the textiles, temperature, maximum spin speed and residual moisture.

After washing the test strips were dried and the reflectance of each of the five stains was measured by a spectral photometer (Figure 1, next page, down right). After the completion of a test cycle the average reflectance-values were derived, which then were summed up to the total reflectance (C_{test}).[5]

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2 All three tested washing machines have a Washing Efficiency Index I_W of > 1.03 as required by the Ecodesign Regulation for washing machines with a capacity > 3 kg. This requirement corresponds to class A according to the former EU Energy Label for washing machines. On the current EU Energy Label the washing performance is not indicated anymore.

3 Annex I of the Ecodesign Regulation [12]: «Household washing machines shall offer to end-users a cycle at 20°C. This programme shall be clearly identifiable on the programme selection device of the household washing machines or the household washing machines display, if any, or both.»

4 Named «partial load» in [11] and [12].

5 Example Test 1b (20°C): average reflectance-value of sebum/pigment: 71.19, mineral oil/black carbon: 47.18, blood: 75.76, chocolate/milk: 71.35 and red wine: 75.54. → Total reflectance Test (C_{test}): 341.02

Fig. 1: test strips with the five standard stains are sewed on the test laundry (top left), the stains get pre-treated with a stain remover (top middle), loading in accordance with EN 60456 (top right), unloading of the washing machine and tearing-off the test strips (down left), drying the test strips (down middle), measuring the reflectance of the stains (down right)

Washing Efficiency Index

The values of the total reflectance by themselves do not have an explanatory power on the washing performance. Relevant for conclusions is the so called «Washing Efficiency Index».

Therefore the total reflectance (C_{test}) was compared with the total reflectance of a reference machine at 60°C ($C_{ref,\ 60°C}$)[6]. This is the same procedure as applied for the calculation of the Washing Efficiency Index I_W in accordance with the Ecodesign Regulation. However, there it is applied for the combined test series of the three standard programmes 60°C full-load (3x), 60°C half-load (2x) and 40°C half-load (2x), while we here applied it on the tested programmes 40°C half-load (same as used for the EU Energy Label and Ecodesign), 40°C full-load, 20°C half-load and 20°C full-load.

The Ecodesign Regulation requires for washing machines with a capacity > 3 kg a Washing Efficiency Index I_W of > 1.03 for the combined test series of the three standard programmes [12].

In this study the value of «> 1.03» is taken as definition and threshold for «clean» in the sense of the Ecodesign Regulation.

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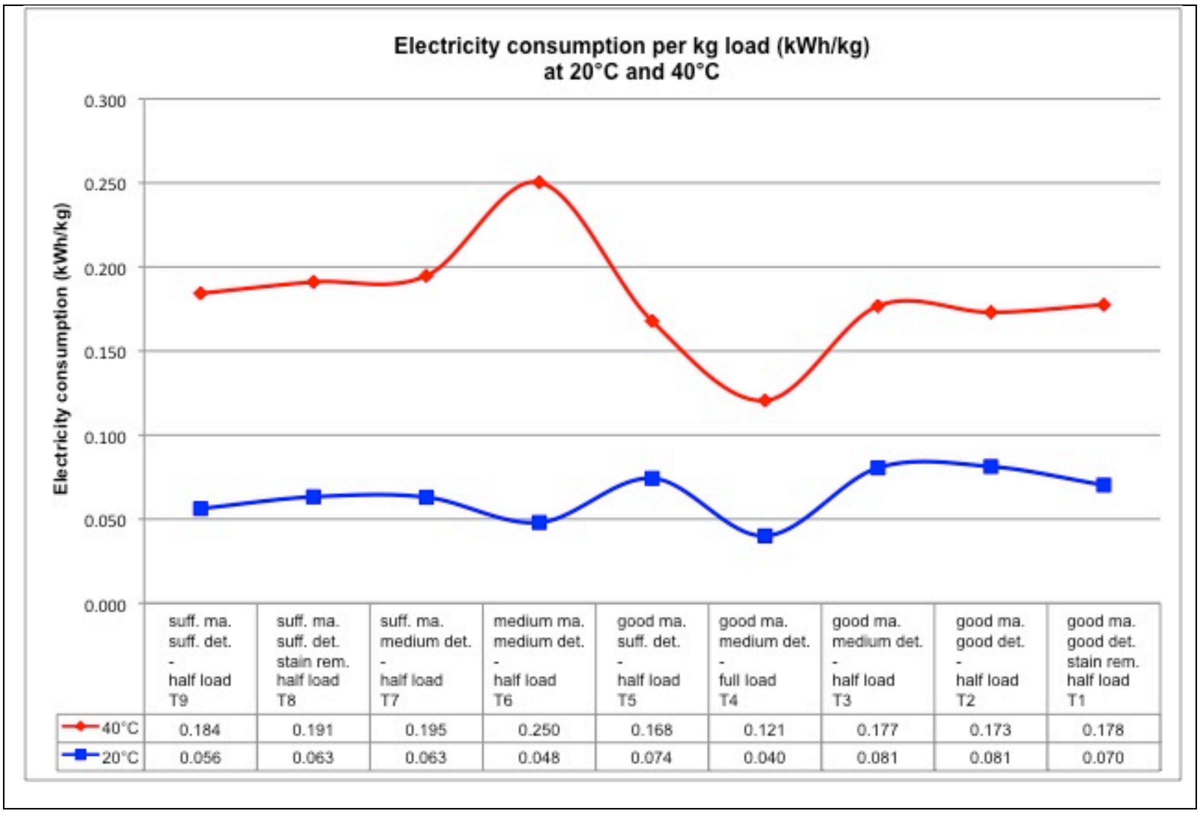
[6] Example Test 1b (20°C): total reflectance Test (C_{test}): 341.02, total reflectance of reference machine at 60°C ($C_{ref,\ 60°C}$): 330.37 → Washing Efficiency Index (C_{test} / $C_{ref,\ 60°C}$) = 1.032

Results and discussion

About 60% less electric energy consumption per kg load at 20°C than at 40°C

A key finding of this study is: washing at 20°C consumes between 53% and 80% less electrical energy per kg load than washing at 40°C (average: 64%, Figure 2). «Cold wash» thus holds a high saving potential.



	suff. ma. suff. det. - half load T9	suff. ma. suff. det. stain rem. half load T8	suff. ma. medium det. - half load T7	medium ma. medium det. - half load T6	good ma. suff. det. - half load T5	good ma. medium det. - full load T4	good ma. medium det. - half load T3	good ma. good det. - half load T2	good ma. good det. stain rem. half load T1
40°C	0.184	0.191	0.195	0.250	0.168	0.121	0.177	0.173	0.178
20°C	0.056	0.063	0.063	0.048	0.074	0.040	0.081	0.081	0.070

Fig. 2 Washing at 20°C uses about 60% less electrical energy per kg load than at 40°C

Good washing performance at 20°C is possible

Looking at Figure 3 shows that the Washing Efficiency Index at 20°C is lower than the one at 40°C (in average 0.1). However, this is mainly due to the shorter programme times of the 20°C-programmes compared to the 40°C-standard cotton programmes, which are optimized for the EU Energy Label and Ecodesign requirements (details see below).

It further can be seen, that the washing performance at 40°C as well as at 20°C steadily increases from the worst tested scenario (left, T9: sufficient machine, sufficient detergent, no stain remover, half-load) to the best tested scenario (right, T1: good machine, good detergent plus stain remover, half-load).

However, the most important result of this study is: the combination of a good machine and a good detergent at half-load with or without stain remover reach at 20°C a Washing Efficiency Index of 1.032 (T1) and 0.994 (T2) respectively[7]. These values would comply with the minimum requirements for cleanliness in the sense of the Ecodesign Regulation (> 1.03 = clean, green horizontal line Figure 3).

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[7] Annex III of the Ecodesign Regulation [12]: Verification tolerances for the Washing Efficiency Index: the measured value shall not be less than the rated value of the Washing Efficiency Index (I_W) by more than 4%.

For a 20°C-programme these results are remarkable because the level of about 1.03 is usually reached by the 40°C-standard cotton programmes at half-load (experience by VDE).[8]
Another interesting finding is: washing at 20°C can reach approximately the same or even better washing results than washing at 40°C.[9]

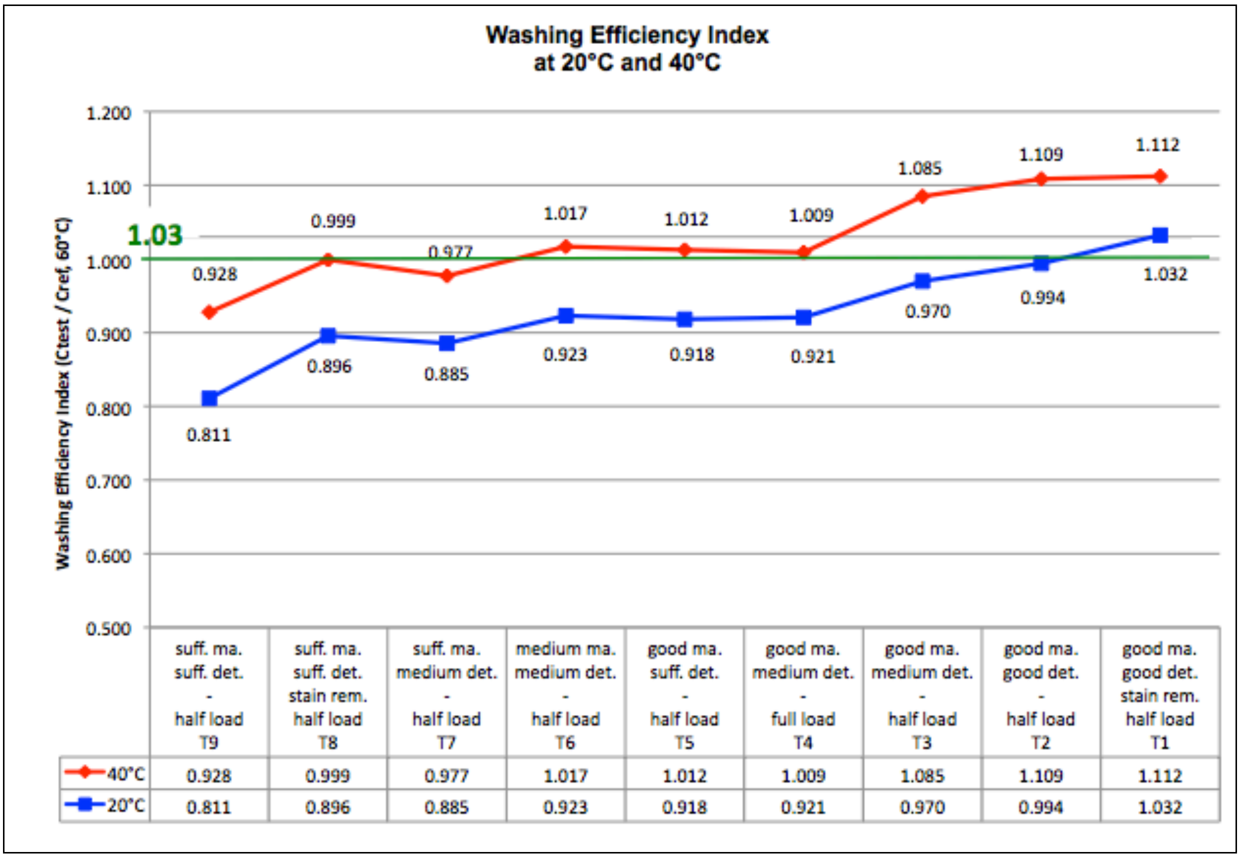

Fig. 3 Washing at 20°C provides good washing results when using a good machine and a good detergent (with or without additional stain remover)

Overall-influence by detergent, pre-treatment of stains, washing machine and loading is higher than the influence by temperature

Figure 4 and Table 2 illustrate that detergent, pre-treatment of stains, washing machine and loading do have an influence on the washing performance at 40°C as well as at 20°C. Summarized:

- Using a good detergent increases the washing result.
- Pre-treating stains raises the washing result, too, especially when using a sufficient detergent.
- The washing result increases with the washing performance of the washing machine.
- The washing performance is better at half-load than at full-load (due to higher mechanical action at half-load).

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[8] Note: The tests for the calculation of the Washing Efficiency Index according to the Ecodesign Regulation are carried out with the medium detergent (IEC A*, EN 60456), while the results of T1 and T2 base on the usage of the good detergent.

[9] Examples: T1 at 20°C (1.032) reaches in six cases better washing results than at 40°C (T4 to T9). T2 at 20°C (0.994) washed in three cases better or approximately as well as at 40°C (T7 to T9).

The overall-influence on the washing performance by detergent, pre-treatment of stains, washing machine and loading is about double than the influence on the washing performance by temperature. (Table 2: From T9 to T1: at 40°C: +0.184 / at 20°C: +0.222; From 20°C to 40°C in average +0.1).

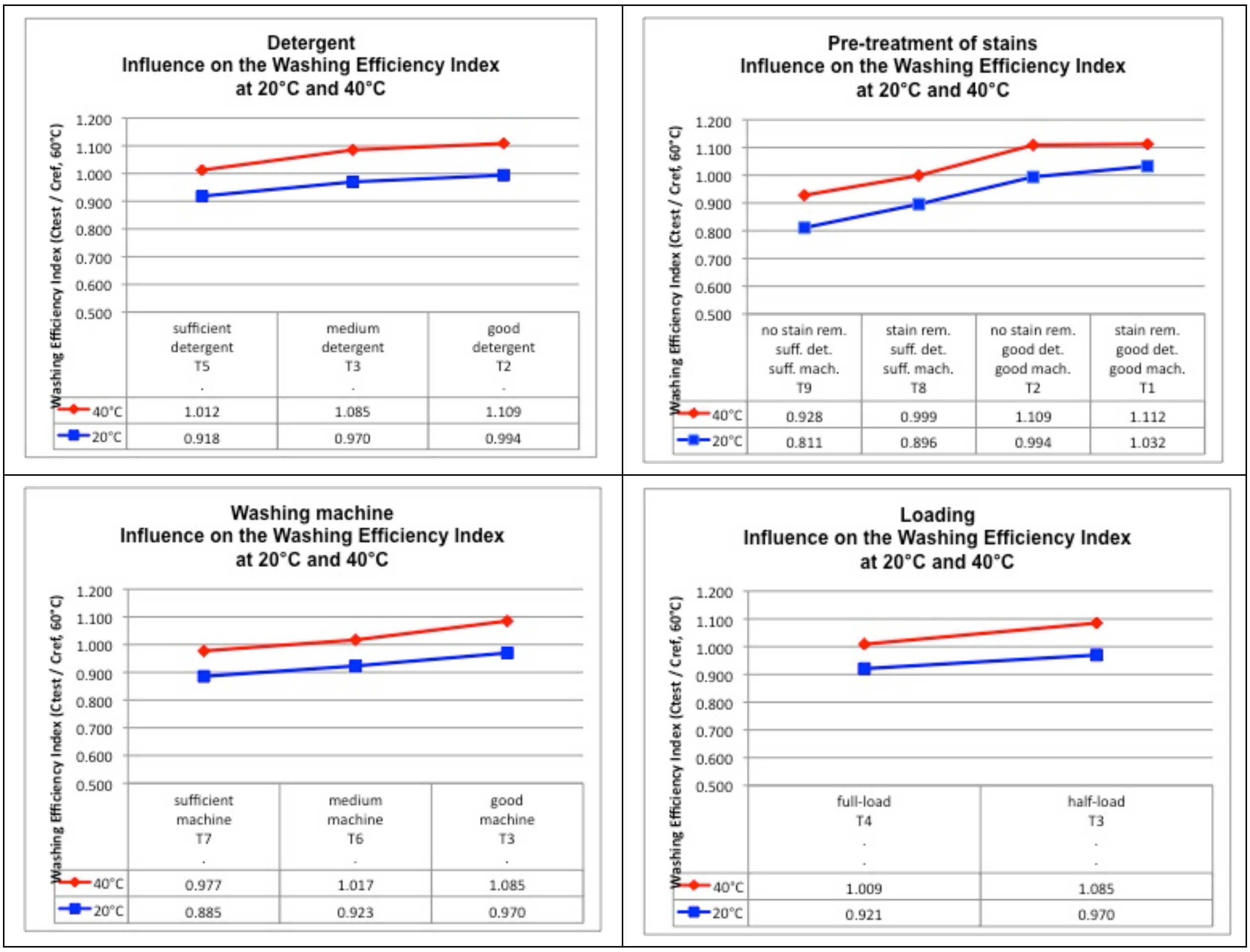

Fig. 4 Influence on the washing performance by detergent (top left), pre-treatment of stains (top right), washing machine (down left) and loading (down right)

Table 2 Overview on the influence on the Washing Efficiency Index by detergent, pre-treatment of stains, washing machine, loading, all parameters together and temperature

Variation of the washing performance due to changes in …	**Washing Efficiency Index**	
	at 40°C	**at 20°C**
Detergent: from sufficient (T5) to good (T2)	+0.096	+0.076
Pre-treatment of stains		
a) Sufficient detergent + sufficient machine: from «no stain remover» (T9) to «with stain remover» (T8)	+0.071	+0.085
b) Good detergent + good machine: from «no stain remover» (T2) to «with stain remover» (T1)	+0.004	+0.038
Washing machine: from sufficient (T7) to good (T3)	+0.108	+0.084
Loading: from full-load (T4) to half-load (T3)	+0.076	+0.049
All parameters: from worst scenario (T9) to best scenario (T1)	**+0.184**	**+0.222**
Temperature: from 20°C to 40°C: in average **+0.1**		

Programme time also influences the washing performance

Programme time differed between the 40°C-standard cotton programmes and the 20°C-programmes. The 20°C-programmes were shorter than the 40°C-programmes (Figure 5). They only lasted between 1.5 and 2.5 hours while the 40°C-standard cotton programmes run between 2 and 3 hours. The 40°C-standard cotton programmes are usually optimized to get a good energy efficiency classification on the EU Energy Label and to meet the Ecodesign requirements on the washing performance. Long programme times help to achieve it (Sinner circle).

Furthermore, programme time differed between the three tested washing machines. The good machine (T1 to T5, Figure 5) had considerably longer wash times than the sufficient one (T7 to T9). It washed at 40°C up to 51 minutes longer and at 20°C up to 1 hour longer than the sufficient one.

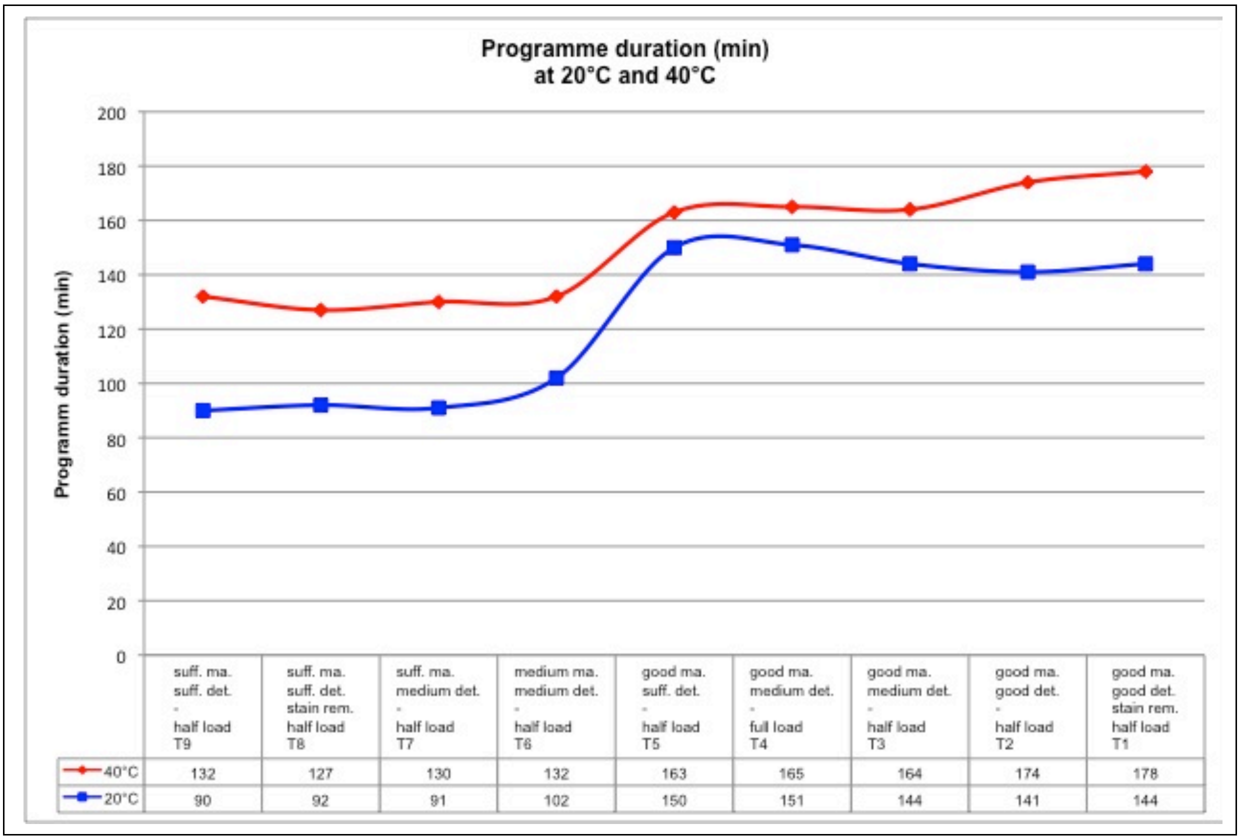

Fig. 5 Programme time differs between the 40°C- and 20°C-programmes and between the washing machines

It is striking that the good washing machine with the comparatively long programme times also reached a better washing performance than the sufficient washing machine with the shorter washing times (Figure 3). Once again this demonstrates well the correlation between programme time and washing performance. The above mentioned differences in the washing performance between 40°C and 20°C can mainly be explained by the shorter programme times of the 20°C-programmes.

Conclusions

- Across the washing arrangements tested, washing at 20°C saved on average about 60% electrical energy compared to the 40°C-programme. Thus, «cold wash» – washing at 15/20°C – holds a tremendous electricity and CO_2 savings potential, which cannot be reached as easily by any other measure in the whole washing process. With an estimated stock of washing machines of about 180 million units in EU-27 and a total electricity consumption of 19 TWh per year[10], «cold wash» could save 11 TWh per year. This equals 2'200 million Euros[11] or the annual production of the German nuclear power plant Emsland [14]. It thus may be worthwhile to rethink our everyday washing routine.

- Washing results depend on a variety of factors: unsurprisingly, washing performance increases with the quality of detergent and with the quality of the washing machine. Pre-treating stains increases washing performance, just as washing at half-load (as opposed to full-load). Also longer programme times positively affect the washing result.

- Good washing performance at 20°C – which would be in compliance with the EU Ecodesign requirements (> 1.03) – is reached when using good machines and good detergent (with or without additional stain remover).

- Though not part of the test, it can be assumed that the potential of «cold wash» is not yet scooped and that the washing performance can be even higher, e.g. with washing machines offering an even better washing performance than the tested one (e.g. as also presented in [6]), even better detergent and with longer programme times at 20°C.

- It has to be kept in mind, that the tests were carried out with standard test laundry, which is heavily soiled. However, our everyday clothing only worn for a few hours or one day usually are only lightly and normally soiled. It therefore is assumed that «cold wash» absolutely is appropriate for this typical type of laundry.

Recommendations

The tremendous but still dormant electrical energy savings potential when using the 20°C-programme is unmatched in the whole washing process and represent an opportunity not to be missed. While the recently launched campaign «I prefer 30»[12] follows the approach to downshift the washing temperature gradually, Topten recommends to reduce the wash temperature right to 15/20°C for lightly and normally soiled laundry. To promote «cold wash», we suggest:

- <u>EU policies</u>: the running revision of the EU Ecodesign Regulation shall include requirements on the washing performance at 20°C. For the consumers it has to be guaranteed that the 20°C-programme – which is required by the Ecodesign Regulation – leads to good washing results.

- <u>Washing machine manufacturers, detergent manufacturers and retailers</u>: active and continued advertisement of «cold wash» for lightly and normally soiled laundry and encouragement of consumers to try it out. Ongoing optimization of the 15/20°C-cycles and of detergent active at these temperatures.

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10 Assumptions according to [13]: 185 cycles per unit per year and 0.57 kWh per cycle based on average 40°C-programme half-load plus 12% for slightly higher load (+10%) and 1°C higher wash temperature. Note by the authors: Electricity consumption would be higher if the assumptions would be based on the EU Energy Label instead (220 cycles and inclusion of the 60°C-programme).

11 Assumption electricity tariff: 0.20 €/kWh. However, there can be large differences depending on country or electric utility.

12 The campaign «I prefer 30» was launched by the International Association for Soaps, Detergents and Maintenance Products A.I.S.E. in 2014 and is supported by a broad range of stakeholders. It aims to raise awareness of the benefits and to support consumers in lowering their wash temperatures. www.iprefer30.eu

- Environmental organizations, consumer organizations, energy agencies: active and continued consumer information on «cold wash» (e.g. with flyers such as «Washing at 20°C is Cool» [7]) and encouragement of consumers to try it out.

- Academia, research institutes, testing laboratories: Publication of studies (consumer and technical), continuing tests on «cold wash», especially for lightly and normally soiled laundry.

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An application of new standard IEC 62552 for household refrigerating appliances energy performance measurements

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Abstract

Within the European Union, the actual enforcement of policies for energy efficiency, energy labelling and EcoDesign is realised on three closely interdependent levels (nationals, European and international). A further action plan is focused on the development of technical standards, strongly related to measurement methods, which constitute the basis for any policy measure.

In the last two decades, there has been a lively evolution of legislation for the domestic refrigerating appliances, which resulted in the attempt of the IEC International Technical Committee 59 to develop a unique and shared measurement method for the evaluation of domestic refrigerating appliances performance. This effort takes the name of the standard IEC 62552:2015, released for the process of consultation in March 2013 [1] and published in February 2015 [2].

The work here presented is related to the released March 2013 version of the IEC standard, preceding the IEC 62552:2015 publication, and will be referred hereafter as the "released IEC standard".

The aim of this paper is: i) to contextualise, analyse and discuss the method proposed by the released IEC standard, particularly focusing on the energy consumption aspects; ii) to describe and discuss the results of a series of tests on a domestic refrigerating appliance, performed on the basis of the new proposed method in ENEA, UTTEI-SISP research laboratories, located in Ispra (VA) Italy.

The tests conducted on a refrigerator/freezer combination sample represent one application of the released IEC procedure, outside the TC59 of IEC, and the obtained results can be used for a further evaluation of the procedure, also in comparison with the one currently into force. Moreover, the analysis provides first insights about the main critical aspects of application, and suggestions for possible refinements of the new IEC method.

Keywords

Household refrigerating appliances, test procedure, IEC 62552:2015.

Introduction

Since the early 1990s, the International Organization for Standardization (ISO) produced the first generation of technical legislation for the performance evaluation of the cold appliances, also following the contemporary technological evolution of products. These standards were adopted in Europe (as EN 153 of 1996) and laid down the foundation for the emerging energy labelling of products and the following requirements of Ecodesign.

In 2005 the original set of ISO standards was revised and harmonised with the ISO 15502 [3], which in Europe was implemented with minor modifications1 by the standard EN 153:2006 [4], adopted as the reference for the European regulations (in the framework of Energy Labelling Directive

[1] Compared to the ISO 15502, the EN 153 fixed (regardless of the refrigerating appliances climate class) the ambient temperature to + 25 ° C for the tests of power consumption, temperature rise time, freezing capacity and ice-making capacity, allowing a direct comparison between appliances with different climate classes. It also introduced a correction algorithm of the energy consumption to take into account the actual ambient temperature deviation (in a climatic chamber), with respect to + 25 ° C.

2010/30/EU and Ecodesign Directives 2005/32/EC, 2009/125/EC) during the years of their full implementation.

In 2007 the responsibility for household refrigerating appliances changed from ISO to IEC and the standard ISO 15502:2005 was reissued as IEC 62552:2007, which is identical to the ISO standard on which it is based. In 2013, with the addition of wine cellars, it was adopted as the EN 62552:2013 [5] by CENELEC.

In general, all of these standards follow a similar test procedure. Firstly, the refrigerator should be tested according to its climate classification: for subtropical regions (N-class) the test is carried out at an ambient temperature of 25.0±0.5ºC. According to these standards, the refrigerator power consumption must be monitored during a period of 24 hours including an integer number of on-off cycles and at least two defrosting cycles. The refrigerator must be instrumented with loading packages whose specific heat is equivalent to that of frozen meat. Some of these packages have thermocouples mounted (known as M-packages). For energy determination, two (or more) tests are usually carried out, one above and another below the reference temperatures (for instance, -18ºC for the freezer compartment and 5ºC for fresh-food compartment) and the energy consumption is calculated from a linear interpolation using both test runs.
Due to worldwide not-negligible differences in regulations, certification schemes and standard measurement procedures[2], the International Electrotechnical Commission, strongly supported by the industry associations, took the lead in proceeding towards converging, harmonised, and widely shared testing and labelling methodologies and procedures.

With this goal in mind, within the IEC Technical Committee 59 (Performance for household and similar electrical appliances) the subcommittee SC59M3 (Performance for household and similar cooling and freezing appliances) was established and the development of a new global standard for household refrigerating appliances commenced in 2006. After several development testing, in May 2013 the subcommittee released for comment a committee draft for voting prIEC 62552 (Edition 2) as the consensus basis of a globally acceptable procedure to test the performance and energy consumption of household refrigerating appliances.

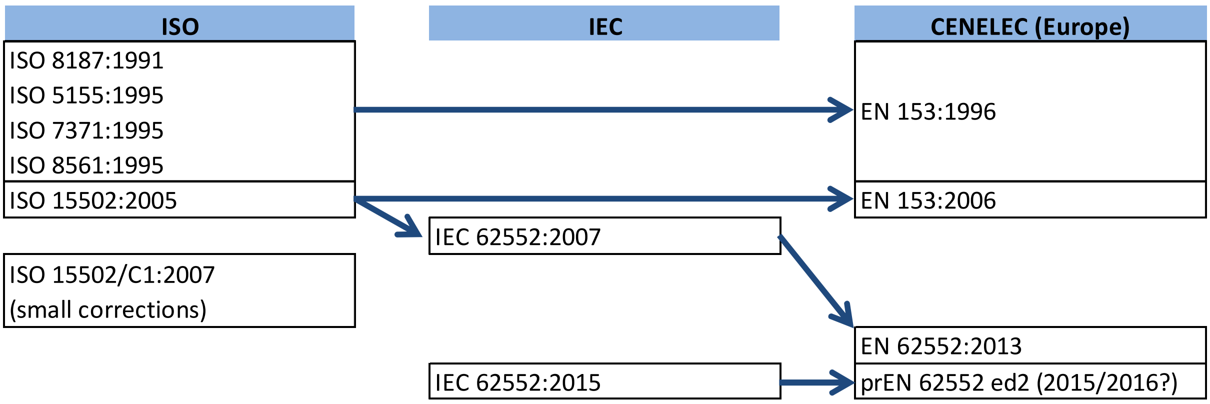

Figure 1: Scheme representing the evolution of the reference standards for evaluating the domestic refrigerating appliances performances.

IEC released Standard (hereinafter named "IEC") is divided into 3 parts, namely: Part 1: General requirements, Part 2: Performance requirements, Part 3: Energy consumption and Volume. The methodological differences with the European current standard (EN 62552:2013 [5], hereinafter named "EN") can be relevant:

- General definitions partly differ: the IEC introduces devices and systems not yet existing or commonly diffused in Europe when the EN was prepared (in particular related to wine cellars).

[2] For instance in USA the reference standard is the ANSI/AHAM HRF 1-2007, in Japan the JIS C9801:2006 and in Oceania the AS/NZS 4474.
[3] Composed of appointed experts by Germany, Italy, UK, Netherlands, USA, Japan, Australia, New Zealand, Brazil and China.

- IEC provides more detailed specifications for equipment, test chambers, general measurement procedures, including the appliances preparation for the tests. Furthermore, the specified measurements uncertainties, instruments accuracies and tolerances are more restrictive.

- Some of the tests are envisaged in EN but not in IEC (e.g. sealing of gasket, mechanical resistance to the doors openings tests) or vice versa (e.g. cooling capacity and pull down tests).

- Target temperatures in the fresh-food compartment differ: + 5 ° C in EN 62552 [5] and + 4 ° C in the proposed IEC.

- Considering the measurement of air temperature in the refrigerating appliances compartments, the prescribed arrangement and type of sensors differ. In particular, according to the EN, the low temperature compartments are always tested by inserting loads. In the IEC, while for storage tests freezer test packages are still used, for the energy consumption test, the low temperature compartments are tested with empty compartments. The compartment temperatures are the average air temperature of all sensors (in copper cylinders) over the specified period.

Regarding the performance tests, the storage test is very similar in EN and IEC, as both standards require loads in the low temperature compartments. Differently, the processing procedures of freezing capacity test diverge. The EN standard tests the ability to freeze the declared load in 24 hours, maintaining the required conditions in the remaining compartments of the appliance. In case the test fails, the load is reduced. The freezing capacity (i.e. the amount of load that can be frozen successfully in 24 hours) is then determined according to different criteria, including proportionality, and taking into account the measured time of freezing. In IEC, the load to be frozen is instead indicated (a light load of 3,5 kg per every 100 litres of compartment). If this load is frozen within 24 hours while maintaining the required conditions in the rest of the unit, then it is possible to declare the 4-stars. The freezing capacity is then calculated with a formula that links the light load to the measured time of freezing.

Concerning the energy consumption tests - the most interesting test regarding the on-going revisions of the European regulations of Energy Label and EcoDesign - IEC declares that the cold appliances are complex thermodynamic products. As such, a large number of factors can influence the energy consumption during the measurement test conditions, and real life normal regimes usage. The key recognised factors are:

1. The operating conditions:

    a. Ambient temperature (T_{amb}) and humidity;

    b. Settings of the thermostats by the user;

    c. User interaction with the device (air exchange due to the doors opening; insertion of hot food or drinks, moisture);

    d. Installation (air circulation, clearance).

2. The design of the product and its response to the operating conditions:

    a. Characteristics of defrost and recovery;

    b. Defrost interval;

    c. Process efficiency of the refrigeration system, in removing the normal heat load;

    d. Quality and level of thermal insulation of doors, walls, seals, etc.;

    e. Operation of the auxiliaries, which can also be influenced by environmental conditions and use;

f. Size, configuration and proportions of the product.

The main objective of the IEC method is to quantify as many as possible elements constituting the actual energy consumption, and aggregate them to reflect the operating conditions and usage patterns in different climatic zones. According to this approach the different States (or Regions) should choose the consumption components, which can be more relevant in their context, and combine them in the most effective-explanatory way. Therefore, IEC does not propose a single unique consumption value with absolute validity, but an interregional comparison scenario based on the test of the elementary components (e.g. the steady state power or the daily consumption).

In this context, the IEC proposal introduces these major changes with respect to the current European standard:

- regarding the energy consumption test, it proposes two tests at different temperatures (16°C and 32°C), rather than at fixed temperature of 25°C (as in EN 62552 [5]);
- additional tests were introduced to estimate the energy consumption associated to specific auxiliary systems (such as the icemakers);
- a load processing efficiency test was introduced for the quantification of the additional consumption due to the insertion of a load at ambient temperature (simultaneously with door openings).

The gap between the IEC and EN methods does not allow an immediate comparison between the results obtained by implementing the two approaches. In particular, it is not possible either to directly compare the daily consumptions, as obtained by different ambient temperature settings and equipment set-ups (thermostat setting of the fresh-foods compartments and basic load of the low-temperature compartments), nor the annual consumptions. The latter, which is not univocally defined, depends by a weighted average between the results obtained at 16°C and 32°C and additional contributions not considered by EN (e.g. related to the load processing).

Table 1: Main differences between the EN and IEC approaches in the quantification of the energy consumption of an appliance for domestic refrigeration.

Test condition	EN 62552:2013 [5]	Released IEC standard [1]
Ambient temperature	+25°C	+16°C and +32°C
Target temperature	Fresh-food: +5°C Low-temperature[4]: -18°C	Fresh-food: + 4°C Low-temperature[5]: -18°C
Load	Present in the low-temperature compartments	Absent
Temperature sensors	Fresh-food: copper cylinder sensor Low-temperature: M-package	Fresh-food: copper cylinder sensor Low-temperature: copper cylinder sensor
Door opening	Absent	A scheduled sequence of door openings is not defined, but an opening is considered during the load processing test (door left open at 90° for 1 min)
Daily consumption	One value (at 25°C) obtained by average of the interpolations on the target temperatures of the different compartments	Two values (at 16°C and 32°C) obtained by interpolation on the target temperature of a compartment with concomitant compliance with the maximum temperatures in the other ones

[4] Taking the warmest temperature of the warmest test package as reference.
[5] Taking the average air temperature as reference.

Annual consumption	Equal to 365 times the daily consumption	Obtained as weighted average of the conditions at 16°C and 32 ° C and as function of indoor conditions and selection of energy contributions to be defined at the regional level

With reference to the definitions shown below in table 2, applying the procedures disciplined by the new standard IEC the following parameters can be derived:

- Steady state power (PSS) in empty mode;
- Additional energy associated with a defrost and recovery period (ΔE_{df}) and defrost interval (t_{df});
- Energy consumption associated to specified auxiliaries (ΔE_{aux});
- Additional energy consumed by the refrigerating appliance during the test to fully process the loaded added ($\Delta E_{additional}$).

From the early contributions the standard calculates the basic daily consumptions (E_{daily} in Wh) at 16°C and 32°C, such as:

$$E_{daily} = P_{SS} * 24 + \frac{\Delta E_{df} * 24}{t_{df}}$$

From which, referring to the example included in the IEC standard, the annual energy consumption (E_{tot}) can be obtained as:

$$E_{tot} = \left(Day_{16} * E_{daily,16°C}\right) + \left(Day_{32} * E_{daily,32°C}\right) + (\Delta E_{aux}) + (\Delta E_{additional})$$

Where Day_{16} and Day_{32} represent the annual number of days equivalent at 16°C and 32°C, for which a calculation procedure is not already defined by the current version of the standard. They should be identified according to the reference climatic conditions by the regulatory bodies which transpose the standard.

Table 2: Definition of the energy performance parameters of the new IEC standard – "Case SS2".

Energy performance parameter	Symbol	Definition
Steady state power [W]	P_{SS2}	Average steady power consumption referred to "Case SS2". It applies to products with a defrost system (with its own defrost control cycle) where the steady state test period of interest starts with a valid defrost and recovery period. In Case SS2 the whole period from defrost to defrost is used to determine the steady state power consumption by deduction of initial incremental defrost and recovery energy. The steady state operation before the initial defrost and before the following defrost are compared and they shall meet the relevant stability criteria.
Steady state temperature [°C]	$T_{SS2,i}$	Steady state temperature in compartment i, that occurs in the steady state test period SS2. Each compartment temperature is determined over the whole defrost control cycle and the cumulated temperature difference during the defrost and recovery in each compartment is subtracted in order to determine the steady state temperature in each compartment.
% compressor Run-Time	CRT_{SS2}	Average percentage compressor run time that occurs in steady state SS2.
Steady state power correct. [W]	P_{SS}	The steady state power used for subsequent energy calculations P_{SS} is based on the measured steady state power after adjustment that takes into account the difference between the measured ambient temperature during the test and the nominal

		ambient test temperature.
Additional energy defrost [Wh]	ΔE_{df}	Additional energy associated with a defrost and recovery period, over and above the relevant steady state power consumption at the same temperature control settings
Defrost temperature change [°C]	$\Delta Th_{df,i}$	Accumulated temperature difference over time (relative to the steady state temperature) during a defrost and recovery period for compartment i.
Additional compressor run-time [h]	Δt_{drj}	Additional compressor run time associated with defrost and recovery period j (over and above the steady state compressor run time that would have occurred).
Defrost interval [h]	t_{df}	Defrost interval (elapsed time) for each temperature control setting and ambient temperature under test.
Load input energy [Wh]	$E_{input\text{-}test}$	Heat energy removed from the processing load during the test.
Load additional energy [Wh]	$\Delta E_{additional\text{-}test}$	Additional energy consumed by the refrigerating appliance during the test to fully process the loaded added.
Load processing Efficiency [-]	$Efficiency_{load,ambient}$	Measured load processing efficiency for the specified ambient temperature, in Wh/Wh (dimensionless). It may be greater than one.
Energy impact of specified auxiliaries [W or Wh]	E_{aux}	Where the refrigerating appliance contains a specified auxiliary (e.g. ice makers), the energy impact of this device is determined and expressed in watts or watt-hours for a range of ambient conditions. These values are then weighted in accordance with regional requirements and conditions in order to provide a relevant estimate of energy associated with the auxiliary.

Applying the new IEC Standard

The tests conducted in ENEA, UTTEI-SISP Research Laboratories [6] of Ispra (IT)[6], represent one of the first applications of the new procedure IEC, outside the Technical Committee 59M of IEC. The results obtained lay down a base for an initial evaluation of the method, and outline potential issues, and proposals for refinement and completion.

The refrigerating appliance chosen for the study is a 2009 refrigerator/freezer combination sample (hereinafter "cmpA"): a cabinet 3-doors modular, equipped with a compartment (FTZ) configurable on six modes (+6°C, 0°C, -6°C, -12°C and -18°C) with the thermostat of the freezer group.

[6] www.enea.it/laboratori-di-ricerca-di-ispra

Figure 2: Photos of cmpA.

Table 3: Main characteristics of cmpA.

Energy class	A
Climatic class	SN/N/ST
Dimensions	width: 60 cm length: 60 cm height: 190 cm
Volumes	gross total: 419 l gross freezer: 123 l net total: 370 l net freezer: 75 l

In this first phase, the testing of the IEC Standard focused primarily on the energy tests described in section 3 of the standard. In particular, for both ambient temperatures of 16°C and 32°C:

- Test named "Energy": referred to Annex B (Determination of stable power and temperature) and C (Defrost and energy recovery and temperature change) of the Standard. Here, we calculated the steady state power and the additional energy consumption due to defrost cycles applying the "Case SS2 approach[7]" (and in accordance with Annex E, the energy test were repeated twice and the results obtained were linearly interpolated);

- Test named "Load", referred to Annex G (Determination of processing load energy efficiency). Here, the load processing efficiencies were calculated.

These tests were conducted for two operation modes of the cmpA:

- Mod1: the freezer thermostat was set up to convert to a freezer (3-stars) also the modular compartment FTZ;

- Mod2: with thermostat setting suitable to convert the FTZ in a fresh-food compartment.

In the second operating mode, cmpA was also tested for the "Storage" test, described in Part 2 of the Standard. In particular, these tests were performed at 16-32°C (instead of 10-38°C, as prescribed by the climate class of cmpA) and the measurement of the electrical power input (not strictly necessary, according the standard) was carried out to achieve a first estimate of the difference/deviation from the

[7] Annex B of IEC 62552-3:2015 defines two possible cases with respect to the determination of steady state power consumption: "Case SS1" applies to products without a defrost control cycle and products with a defrost system where the defrost control cycle is long and the steady state test period of interest may not be bounded by defrost and recovery periods; "Case SS2" applies to products with a defrost system where the steady state test period of interest commences with a valid defrost and recovery period.

value obtained with the currently followed measuring methods, resulting from conducting the consumption tests in “empty” mode.

Table 4: List of the tests carried out on cmpA.

Test name	Operation mode	T_{amb}
cmpA_Mod1_Energy16-a	Mod1	16°C
cmpA_Mod1_Energy16-b	Mod1	16°C
cmpA_Mod1_Load16	Mod1	16°C
cmpA_Mod1_Energy32-a	Mod1	32°C
cmpA_Mod1_Energy32-b	Mod1	32°C
cmpA_Mod1_Load32	Mod1	32°C
cmpA_Mod2_Energy16-a	Mod2	16°C
cmpA_Mod2_Energy16-b	Mod2	16°C
cmpA_Mod2_Load16	Mod2	16°C
cmpA_Mod2_Storage16	Mod2	16°C
cmpA_Mod2_Energy32-a	Mod2	32°C
cmpA_Mod2_Energy32-b	Mod2	32°C
cmpA_Mod2_Load32	Mod2	32°C
cmpA_Mod2_Storage32	Mod2	32°C

The experimental settings of the climatic room and of the sample test (for each type of test) were defined in accordance with the procedure of the released IEC Standard:

- For the Energy and Load tests, both the fresh-food and the FTZ compartment were instrumented with three Pt100 (type A + copper cylinders) and the low-temperature compartments with 5 sensors of the same type.

- For the tests of Load processing 6 half-litres bottles of water (at room temperature) were used in the fresh-food compartment (2 bottles per shelf) and an ice-making tray, filled with 150 cl of water (at room temperature), was loaded both in the low-temperature and FTZ compartments. To allow the loads to be inserted into the appliance, the doors of the compartments were opened by 90° for 1 minute.

- In the Storage tests, the setting of the freezer was changed, removing the Pt100 sensors and adding a stabilised load of 24 kg composed by 44 standard packages (0,5 kg each) and 4 M-packages, placed in the four corners of the compartment.

Relating to the tests preparation phase, it is worth noting that the main problem introduced by the new procedure is to perform the consumption tests in "empty" mode. Compared to the existing measurement procedures, a longer time for the sample preparation is needed for the IEC. The reason relies on the requirements to install the air temperature sensors (copper cylinders of with Pt100) in the low-temperature compartments (not loaded with packages as in the current EN standard), and to build appropriate auxiliary systems to support the sensors according to specified geometries (fig. 3d).

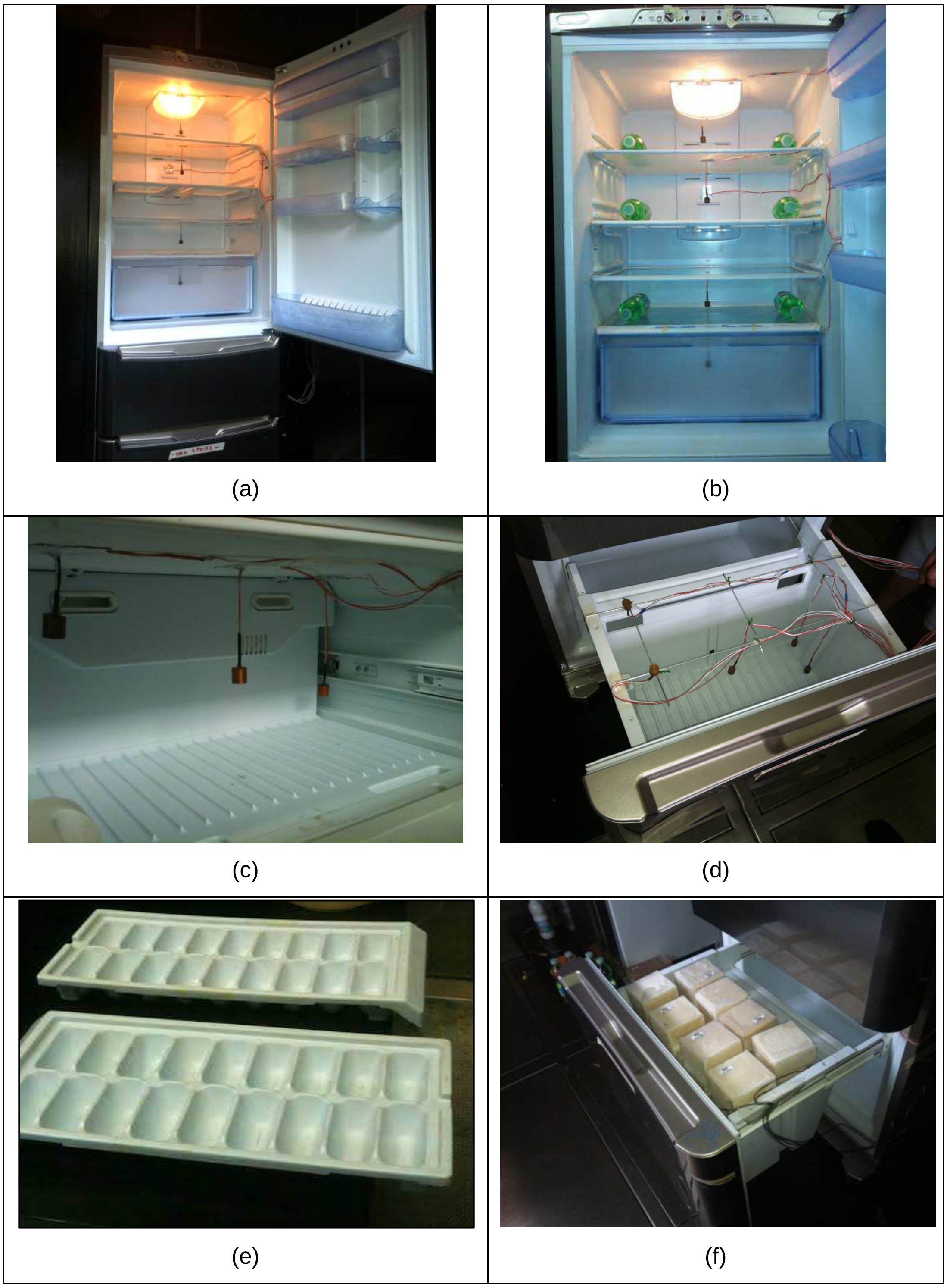

Figure 3: a) Setting of fresh-food compartment; b) Load test in the fresh-food compartment; c) Setting of the FTZ compartment; d) Setting of the freezer compartment; e) Ice making trays used in the freezer during the Load tests; f) Load of the freezer compartment during the Storage tests.

Results obtained

Final results are presented below in table 5. From the results obtained, we propose the following considerations:

- For the tested appliance, the steady state performances strongly depend on the ambient temperature: from 16°C to 32°C, the power (P_{SS2}) increases by about 120% and the compressor run-time (CRTSS2) of almost 110%.

- The parameters linked to the defrost cycles are greater at low compressor run-times, and at 16°C ambient temperature. From 16°C to 32°C, ΔE_{df} decreases by 10% and Δt_{dr} by about 60%.

- Defrost cycles seem not to significantly affect the compartments temperature as the measured temperature variations were negligible;

- For the tested refrigerator/freezer sample, the defrost interval and the load processing efficiency are weakly dependent on the ambient temperature and the operating mode.

- Following the Storage test of the new procedure, the capacity to maintain a frozen load is not guaranteed at the measured energy performances. The deviation from the prescribed thresholds (maximum temperature at stationary conditions of the freezer compartment of -18°C, and -15°C during the defrost cycles) is greater for low ambient temperatures (16°C), which were associated to low compressor run-times.

Table 5: Summary of final results (values resulting after the interpolation). The symbols refer to the original ones, used by IEC.

Performance parameter		Symbol	Mod 1		Mod 2	
			16°C	32°C	16°C	32°C
Steady state power [W]		P_{SS2}	36.9	80.1	32.8	73.9
Steady state temperature (average) [°C]	fresh-food	$T_{SS2,unfrozen}$	4.00	4.00	4.00	4.00
	freezer	$T_{SS2,frozen}$	-21.09	-20.95	-19.56	-18.94
% compressor Run-Time		CRT_{SS2}	41%	84%	36%	74%
Steady state power correct. [W]		P_{SS}	37.1	80.1	32.9	73.5
Additional energy defrost [Wh]		ΔE_{df}	92	81	82	74
Additional compressor run-time [h]		Δt_{dr}	0.66	0.23	0.62	0.29
Defrost interval [h]		t_{df}	30.44	30.66	30.21	30.39
Load input energy [Wh]		$E_{input\text{-}test}$	71	142	69	134
Load additional energy [Wh]		$\Delta E_{additional\text{-}test}$	49	131	59	126
Load processing Efficiency [-]		$Efficiency_{load,ambient}$	1.09	1.09	1.18	1.06
Storage check [°C]	$T_{ma,unfrozen}$		n.a.	n.a.	6.50	3.97
	max $T_{SS2,frozen}$		n.a.	n.a.	-15.20	-17.44
	max $T_{df,frozen}$		n.a.	n.a.	-13.64	-15.52

By applying the IEC method for calculating the daily consumption, we obtained the following results shown in figure 4, with an increase of about 110%, from 16°C to 32°C, and a reduction of 10% from Mod1 to Mod2.

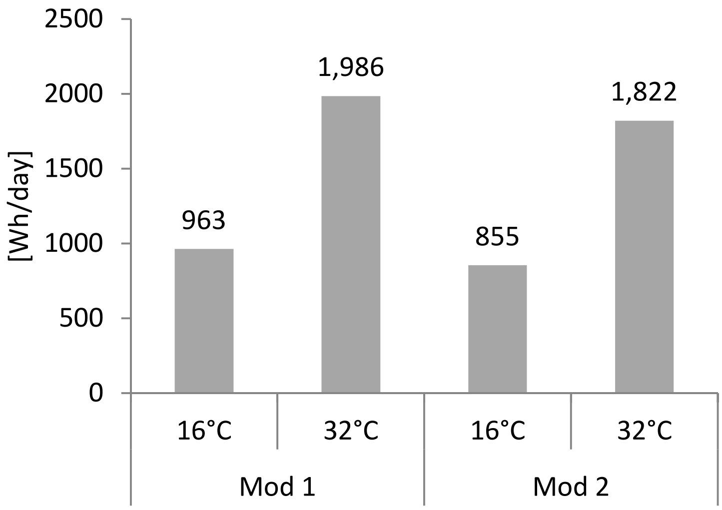

Figure 4: Daily energy consumption for the considered ambient temperatures, and operating modes.

Concerning the Storage tests (as discussed above, it was performed at 16-32°C and we also measured the power consumption), we compared their results with those obtained with the Energy tests, at the same setting of thermostats (see Tab. 5). Due to the insertion of the stabilised load in the appliance low-temperature compartments, we observed that:

- The steady state power increases appreciably (+ 28%) only in correspondence of the ambient temperature of 16°C;
- The additional energy defrost increases more (+ 21% compared to + 6%) for T_{amb} of 32°C;
- The average temperatures of the compartments, in steady state conditions, may also vary considerably: + 48% in the fresh-food compartment at ambient temperature of 16°C.

Table 6: Comparison between the Energy and Storage tests (at the same thermostat setting).

Performance parameter		16°C		32°C	
		Energy	***Storage***	***Energy***	***Storage***
Steady state power [W]		31.5	40.4	74.6	74.3
Steady state temperature (average) [°C]	fresh-food	4.39	6.51	3.90	3.91
	freezer	-19.08	-17.85	-19.56	-19.25
% Compressor Run-Time		34%	44%	75%	73%
Steady state power correct. [W]		31.4	40.5	74.2	74.3
Additional energy defrost [Wh]		87	92	53	64
Additional compressor run-time [h]		0.64	0.69	0.17	0.26
Defrost interval [h]		30.24	30.24	30.38	30.47

The design and performance optimization of the tested refrigerator/freezer sample was carried out in reference to the EN 62552:2013 [5] standards (in particular at an ambient temperature of 25°C). Therefore, deviations between its actual operational mode and the one required by the new IEC approach (at 16°C and 32°C) are predictable. Having said this, it is interesting to note that, in this study, the acceptability conditions imposed by the new standard were satisfied.

Conclusions

We presented the need to standardise the various labelling and control schemes developed in the last twenty years worldwide, and the framework of the new IEC methodological approach. Differently from the current EN standard the IEC approach is based on the quantification of the specific factors majorly contributing to the domestic refrigerating appliances energy consumption in real on-site conditions. In particular, to better approximate the real performance of domestic refrigerating appliances, the results interpolation at local/regional levels and the introduction of specific tests for quantifying the consumption due to a processing load can be relevant innovative approaches to include into the new standards.

Regarding the energy consumption tests conducted in this study, we observe that the choice to remove the frozen and stabilised load from the low-temperature compartments could introduce a number of potentially critical issues, such as: a more complex measurement setting procedure in these compartments; a discontinuous approach with respect to the existing standards; the risk to separate the energy performance of a refrigerating appliance from its ability to maintain a frozen load.

In this study, we further observed that, it was difficult to ensure the acceptability condition, which the IEC standard defines for the maximum deviation between the average powers of two periods preceding two consecutive defrost cycles, namely 1 W and/or 2%. Further testing should prove this value.

As an outlook for the proposed new methodology, it is necessary to complete the calculation procedure for the annual energy consumption related to the local/regional scale, and based on ambient conditions characterising the European regions (e.g. indoor temperature, outdoor temperature). This would introduce continuity with the previous measurement standards by allowing the comparisons of the annual energy consumptions, currently not feasible to perform.

Due to the relevance and impact of the new proposed IEC standard, we advise further analyses and testing. Results and comments should be collected to produce a robust database for tests-supported revision procedures and improvements.

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Interoperability activities for Smart Home Environment

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Abstract

Standardization Committees like CENELEC TC 59X ´Performance of household as well as similar electrical appliances´ and consortia are working on Smart Home and interoperability standards. It is the intention of CENELEC TC 59X /WG 07 to define a Smart Home/Smart Grid standard for Home Appliances, based on the scope

- *Standardization work to enable domestic appliances to improve functionality through the use of network communication.*
- *Examples of network communication include smart grid, smart home and home network.*

The main difference between Single Home Appliances and Smart Appliances in a Smart Home/Smart Grid environment is the dependency on networked systems with different stakeholders like <u>Grid operators</u> via <u>Home and Building Managers</u> realized by lots of <u>different manufacturers</u>.

This means that a Smart Appliance is not anymore a stand-alone device but embedded in a communication system with different other Smart Devices like Smart heating systems, Electric vehicles etc.

In this context <u>interoperability</u> is key to ensure the success of Smart Grid and Smart Home solutions. A customer of a Smart Appliance does not want to be confronted with technology, he needs solutions. Having this in mind, interoperability requires a kind of common architecture model to enable communication between different devices as well as neutral data model and messages to be understood by Smart Devices (like Smart Appliances) independent from different manufacturer.

As this target influences the requirements of the whole chain from the interface of the Grid into the premises, the home & building management and the Smart Devices, CLC/TC 59X/WG 07 ´Smart household appliances´ has liaisons with IEC/TC 57/WG 21 ´Interfaces and protocol profiles relevant to systems connected to the electrical grid´ which is dealing with the definition of the interface of the grid to the premises and CLC/TC 205/WG 18 ´Smart household appliances´ which is in charge with in-house distribution and management.

On the other side, alternative alliances started the last two years, to develop own smart home communication solutions. These alliances like **Allseen/Alljoyn**, **Apple Homekit**, **Google Nest**, **OIC (Open Interconnect Consortium)** and others will influence and may harm interoperability.

Furthermore, initiatives like EEBus Initiative or Energy@home support international public standardization like IEC/TC 57, CLC/TC 205 and IEC/CLC/TC 59.

This report describes the different fields of Smart Home communication to ensure interoperability. Next to this most of the relevant stakeholders like IEC, CENELEC standardization bodies and alliances and their targets towards interoperability are summarized. Finally, one European initiative is described as a starting point to harmonize different initiatives towards one interoperable solution.

Main pillars of interoperability

Interoperability in the context of Smart Home describes the capability of Smart Devices in a Smart Home & Building environment to behave equivalent independent from a specific manufacturer.

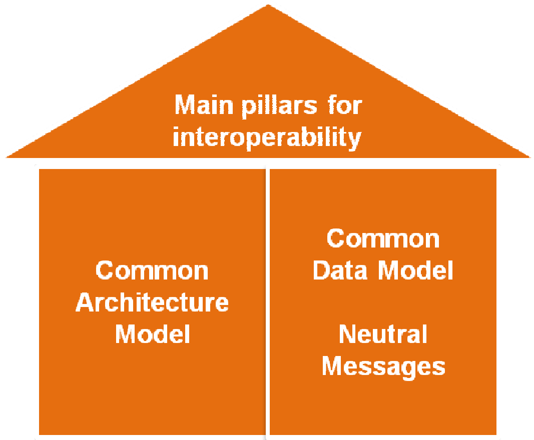

Figure 1: Main pillars of interoperability, [1], [7], [8].

Figure 1 lists the main requirements for interoperability:

- a common architecture model and
- common, neutral data models to ensure common understanding of signals and messages.

Common data model / neutral information to be exchanged

Equivalent behavior of Smart Appliances on an advice or a request is based on a common understanding of this information. This needs to be independent from the way of transport from source to destination. This information can be translated by writing letters on a sheet of paper, put it in an envelope and send it to the addressee or you can translate the information into a morse code and send it with a morse code pad on a two-wire line.

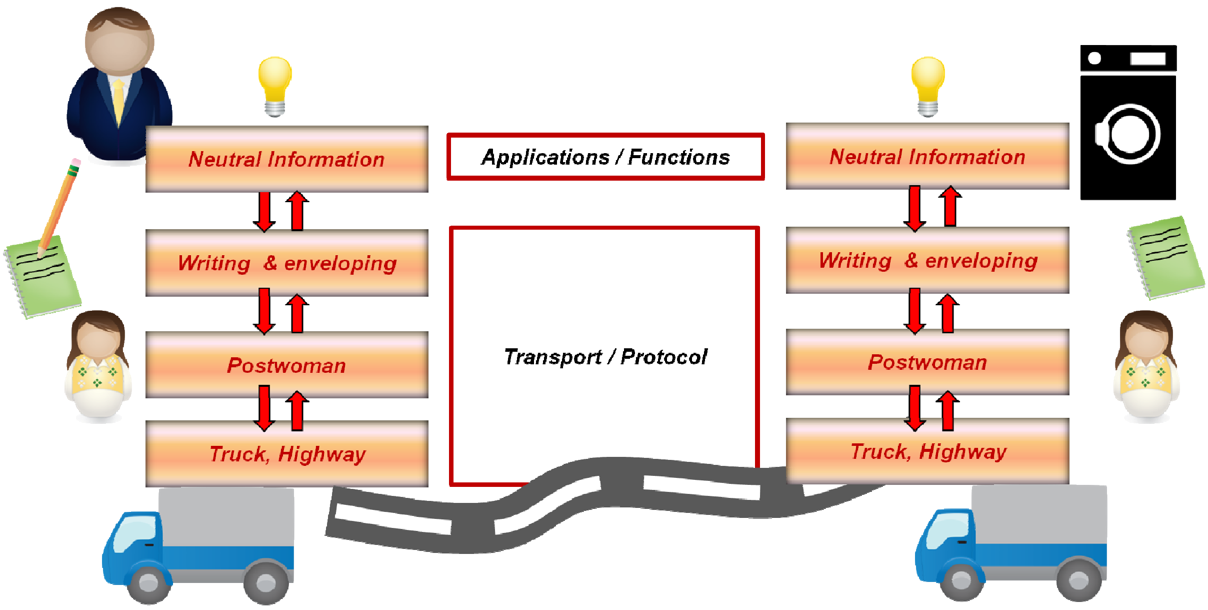

Figure 2: Level of communication, [7], [8].

The information still remains the same. That's the reason why we are focusing on common, neutral data models and neutral information. These data are the semantic of the message we want to exchange.

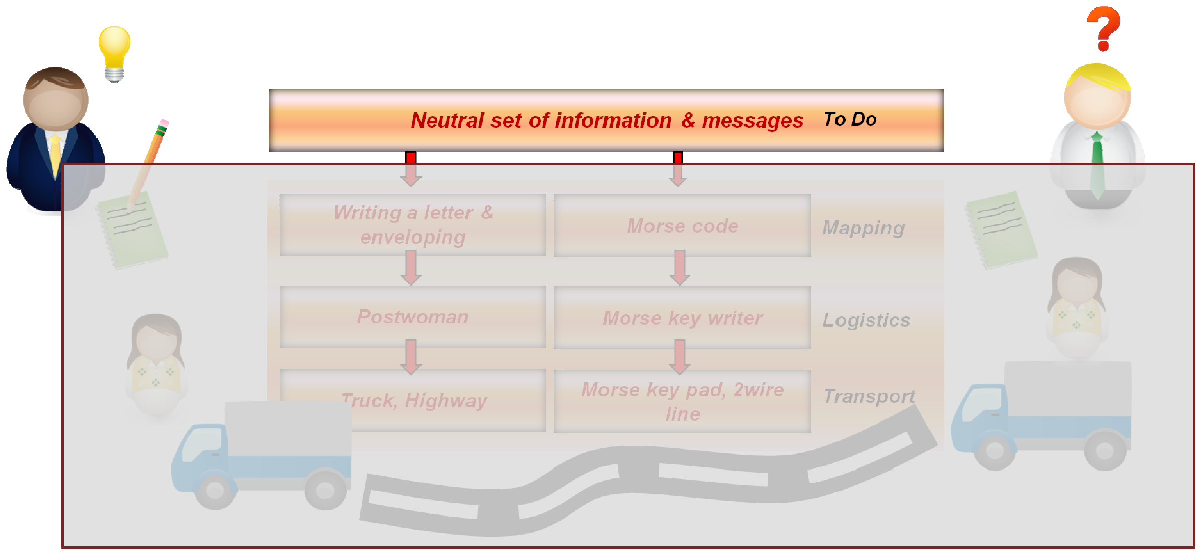

Figure 3: Focus on Neutral information and messages, [7], [8].

Common Architecture model

The common architecture model describes the roles and responsibilities in the context of neutral information handling, the mapping onto specific transport capabilities and the transport.

At EEDAL´13 conference [6] it was reported that the common architecture model is based on the Smart Grid Architecture Model of the Smart Grid Coordination Group (SG CG), see Figure 4 and [5].

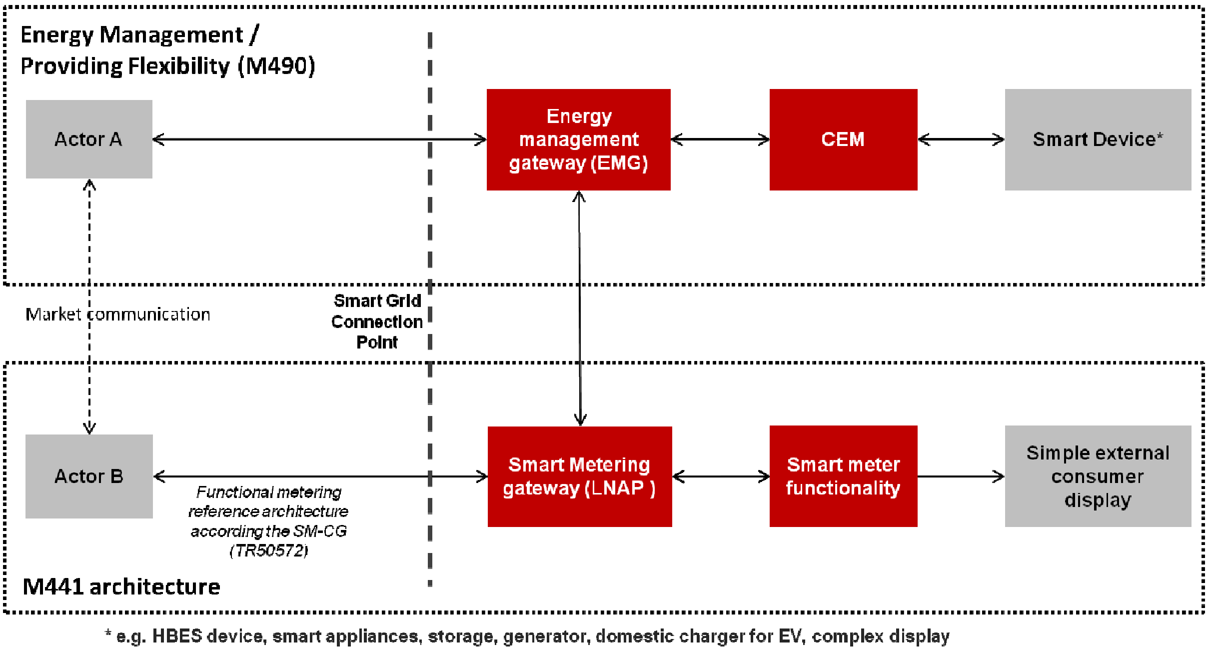

Figure 4: Smart Grid Architecture Model according to [5].

The main part of this architecture model is the so called Customer Energy Manager (CEM). As central management function it decides and manages based on information coming from the Smart Grid and from Smart Devices. These information are represented neutrally with common data models as described above.

Neutral information will be mapped onto domain specific protocols like ZigBee, KNX, SHIP (Smart Home IP Bus) to exchange information with attached Smart Appliances as shown in Figure 5.

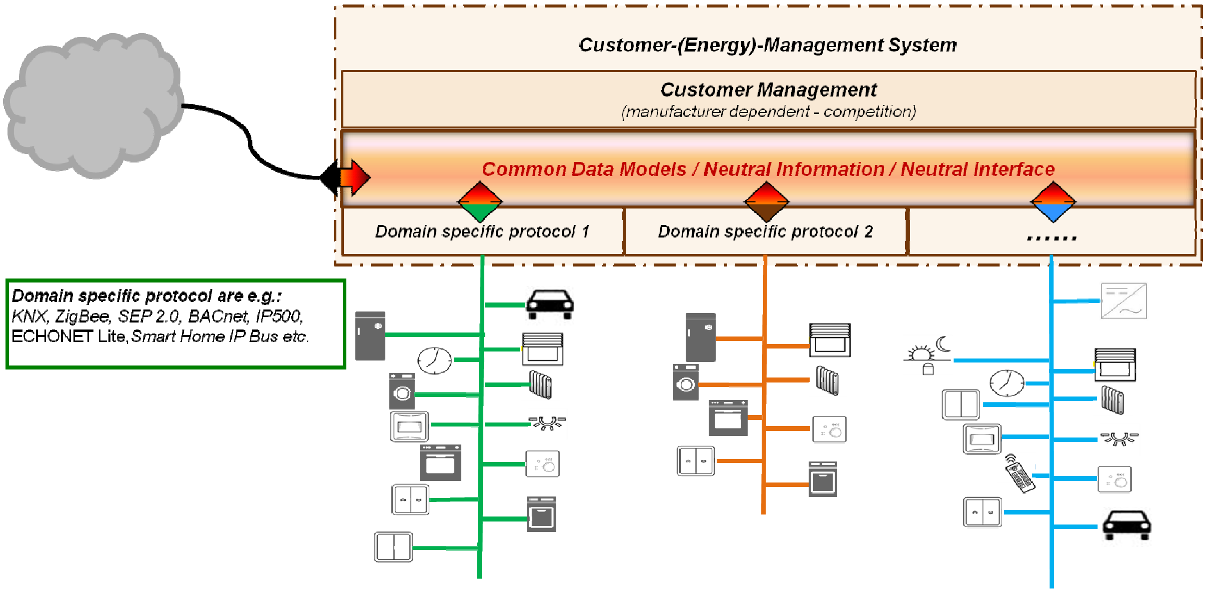

Figure 5: Common Architecture Model, [1], [7], [8].

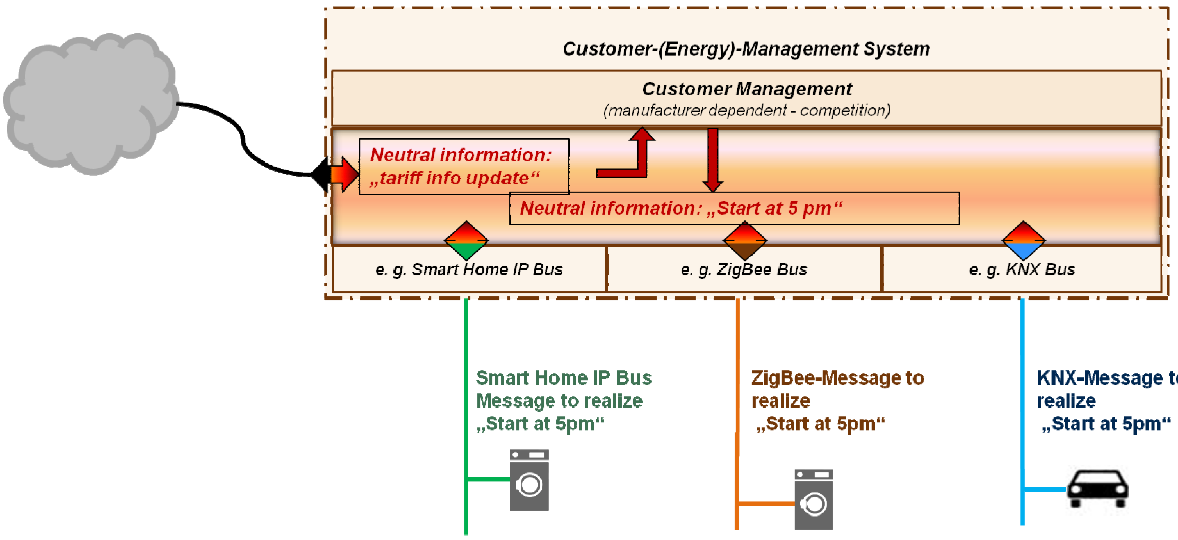

Figure 6: Mapping of neutral information onto domain specific protocols, [1], [7], [8].

Figure 6 shows the mapping of the information “Start at 5pm” onto 3 different communication protocols (like SHIP, ZigBee, KNX). Even if the type of message transport is different (e.g. verbal, written letter or using a morse code), the semantic is the same and the device starts at 5pm. See also Figure 5.

Use cases & Requirements

Since a couple of years many standardization bodies are collecting user stories and use cases to describe Smart Home user scenarios and possible solutions, e.g. using flexibility management in order to use the own DER energy (Distributed Energy Ressource e.g. photovoltaic system on the roof).

The Technical Report IEC 62746-2 [1] lists a number of user stories, use cases and further requirements.

Such a user story is that the customer wants to let the CEM manage the starting time of the dishwasher when the own photovoltaic system provides enough energy. In this story the dishwasher needs to inform the CEM about calculated washing time and the energy consumption during that time. With this information and the forecast from the PV system, the CEM can calculate the best starting time and informs the dishwasher to start at the proposed time.

The main purpose of user stories and use cases is the extraction of necessary information to be exchanged, which means the necessary data models.

For the example of flexible start of dishwasher with own photovoltaic system these are at least the information about starting time, finishing time, energy consumption etc.

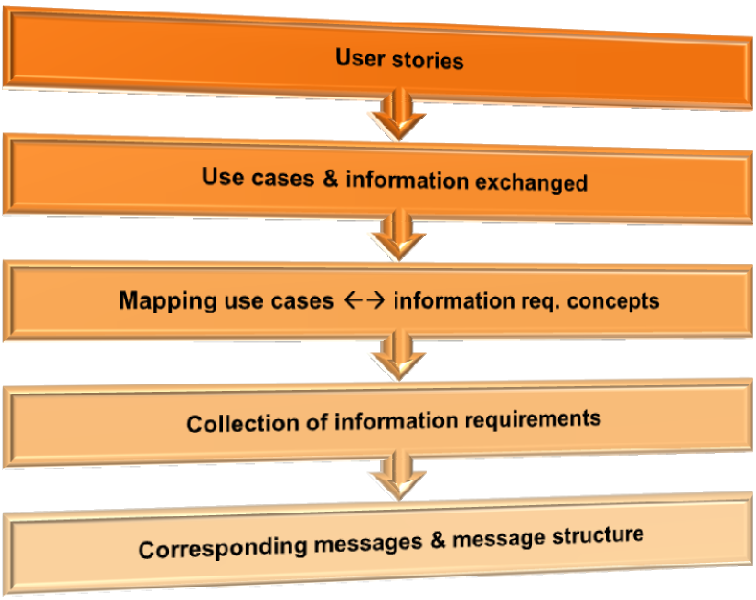

Figure 7: Use Case & Requirements process, used in IEC 62746-2, [1], [7], [8].

It is easy to define the necessary information for a switch, e.g. on, off and maybe toggle.

For other purposes it is much more complicated to get a common agreement of necessary information about energy consumption over time like we have requested with the example of the dishwasher to be managed by photovoltaic system.

Therefore, another target of this process is the definition of specific profiles like the Power Profile in Figure 8 or a Temperature Profile in Figure 9 as a prerequisite for the definition of data models and information to be exchanged.

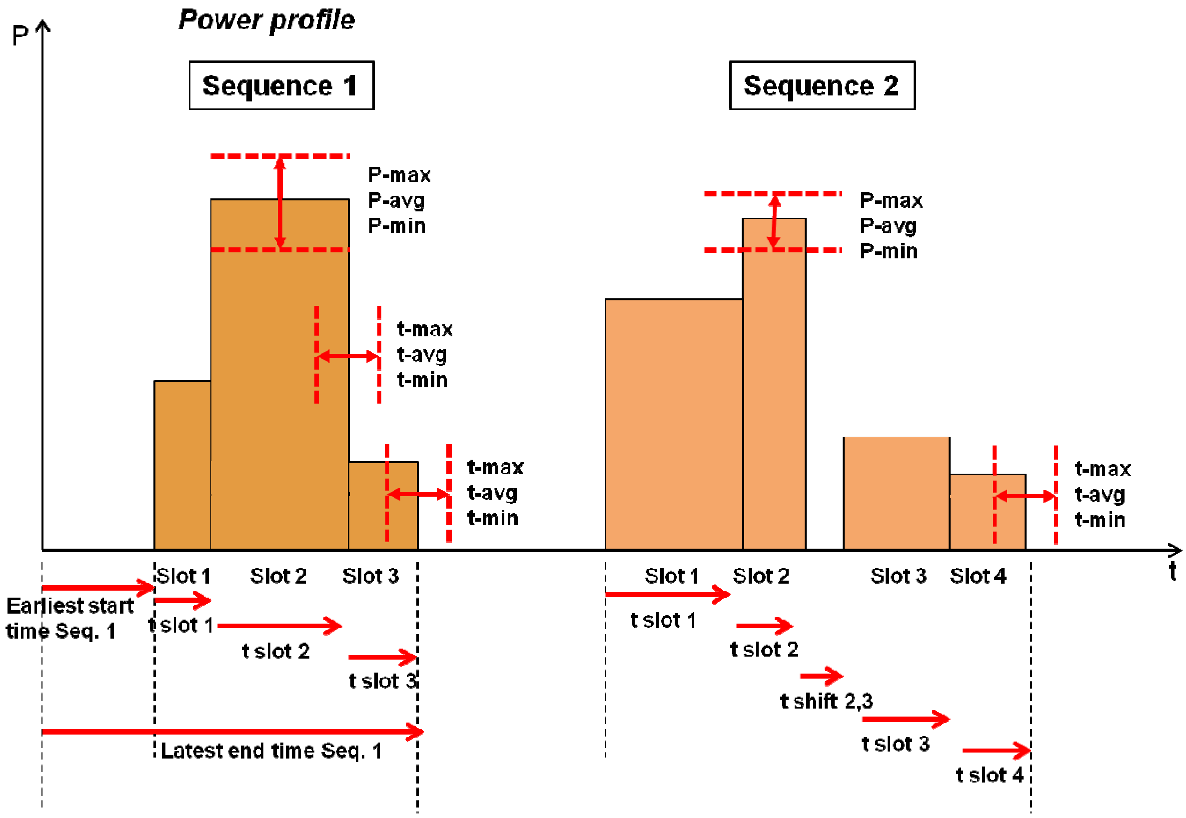

Figure 8: Power profile, [1], [7], [8].

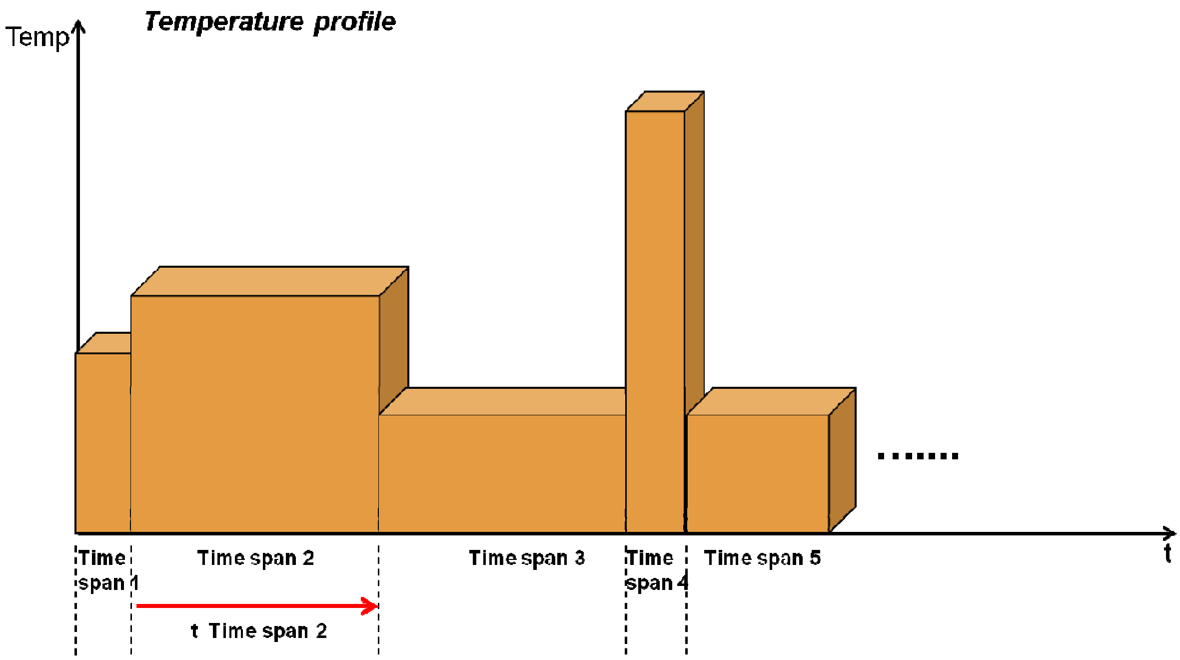

Figure 9: Temperature profile, [1], [7], [8].

These profiles describe the definition of specific dates in the context of a process. As an example: a power consumption sequence of a washing machine may consist of 10 min with 200 W to start the washing cycle, 50 min with 2 kW to heat the water, another 20 min with 300 W to rinse the laundry and finally 10 min with 400 W to spin the laundry.

Data model description

One of the most important tasks to ensure interoperability is the definition of necessary information to be exchanged between partners like Smart Appliance and CEM as already mentioned earlier.

On a high level information to be exchanged can be summarized within tables as shown in the following Table 1

Table 1: Example of Data Model description, [9]

Element name	Data range	M/O/ NV/C	Explanation
suiteId		M	SHALL be present and set to "SmartEnergyManagementPs".
suiteDataGroup		M	SHALL always be present and state "smartEnergyManagementPs_Information".
	List of data group [0..unbounded]	O	Creates a new list of "alternatives" groups, with mutually alternative powerSequences each. SHALL only be left out, if no such group is present.
"alternatives". "powerSequence". powerSequenceDescriptionData		M	General description on the power sequence. SHALL be present.
"alternatives". "powerSequence". powerSequenceDescriptionData. sequenceId	xs:unsignedInt	M	SHALL state an endpoint-wide unique sequence identifier.
"alternatives". "powerSequence". powerSequenceDescriptionData. description	xs:string (1..60 characters)	O	If used, should state a textual description for this power sequence.
"alternatives". "powerSequence". powerSequenceDescriptionData. powerUnit	Enumeration: see Annex A - Units	O	For electric power, the element powerUnit SHALL be omitted and kW SHALL be assumed as unit for the value implicitly. For any other power type, the unit SHALL be stated explicitly.

The more precise and reusable way is to use different kind of description like UML (Unified Message Language) or XSD (XML Schema Definition), most of the time being part of a tool landscape. The following Figure 10 shows an UML example with data model and cardinalities and a XML Schema Definition (XSD).

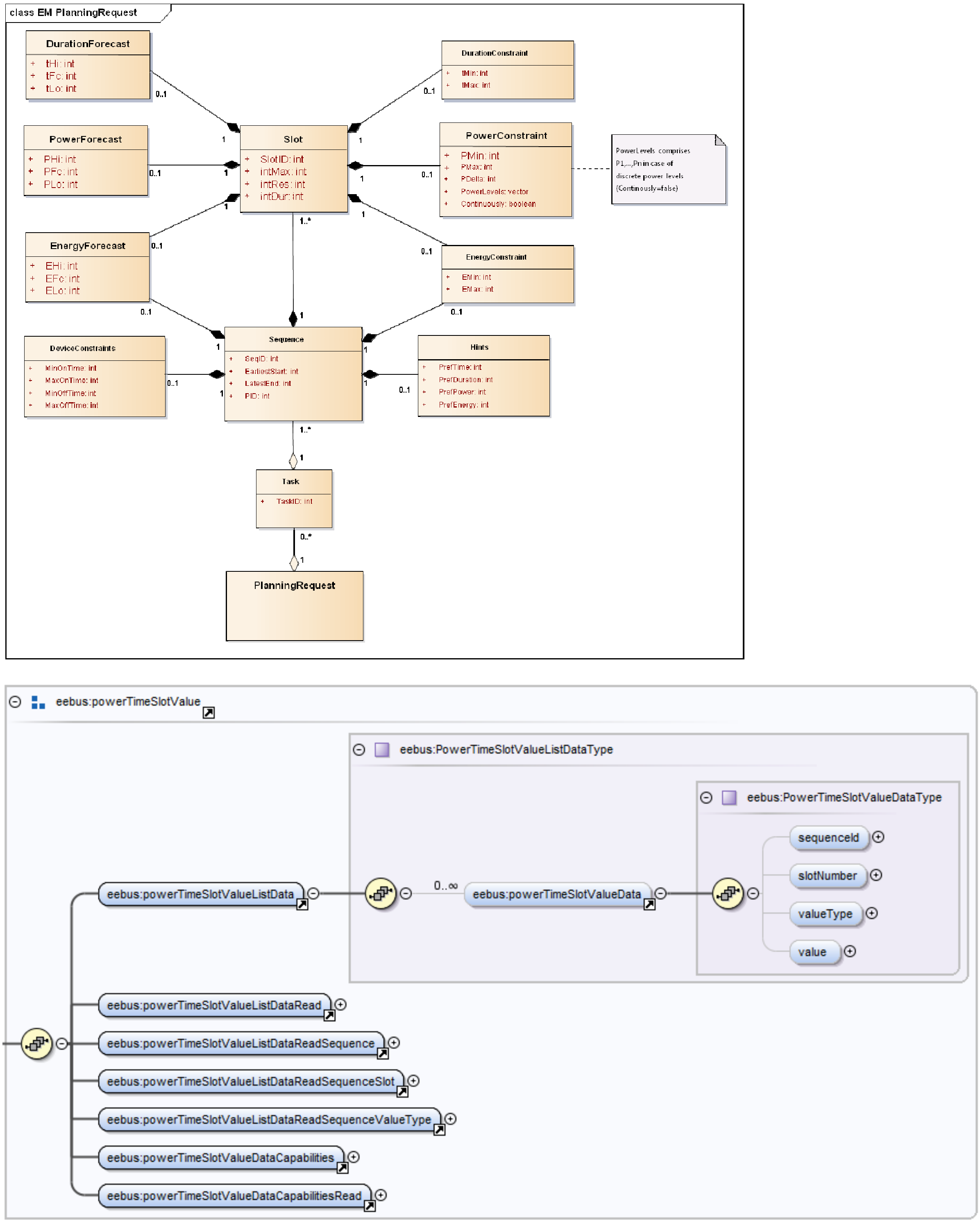

Figure 10: Example of Data Model, described in UML and XSD, [9].

This paper does not prefer a specific method to model and describe data models. As it has been shown there are different ways of doing it.

However data model descriptions are minimum requirements to enable interoperability.

Standardization bodies and alliances engaged in Smart Grid and Smart Home Standardization

Since several years main international standardization bodies e.g. from IEC and CENELEC are working on different areas of Smart Grid and Smart Home standards.

Main contributors are e.g.:

- IEC/TC 57/WG 21, working on interface from the Smart Grid into the premises, Smart Grid Connection Point
- CLC/TC 205/WG 18, working on CEM, Home & Building Management
- CLC/TC 59X/WG 07, working on Smart Appliances, white goods
- IEC/TC 59/WG 15, working on Smart Appliances, test requirements.

Alliances and consortia are also supporting international Smart Home standardization like:

- EEBus Intitative (use cases, common data model, connectivity protocol SHIP)
- Energy@Home (use cases)
- KNX Org (use cases, mapping to KNX)
- BACnet (use cases) and
- others.

Figure 11 presents an overview of international standardization bodies where figure 12 lists the interfaces of the common architecture model and related responsible bodies.

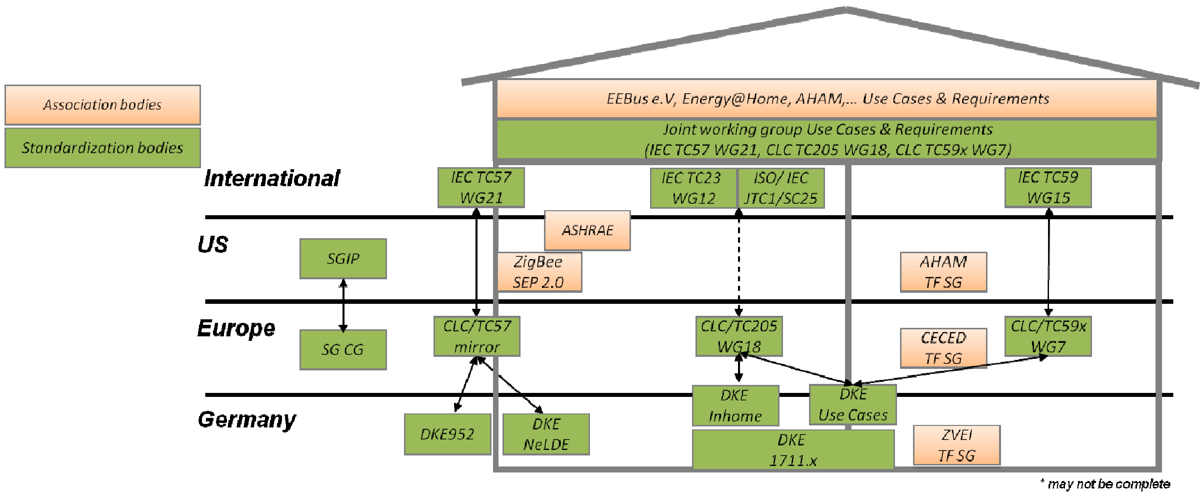

Figure 11: Main international standardization bodies, [7], [8].

Note: This summary is focused on international and European Standardization bodies and does not imply to be complete!

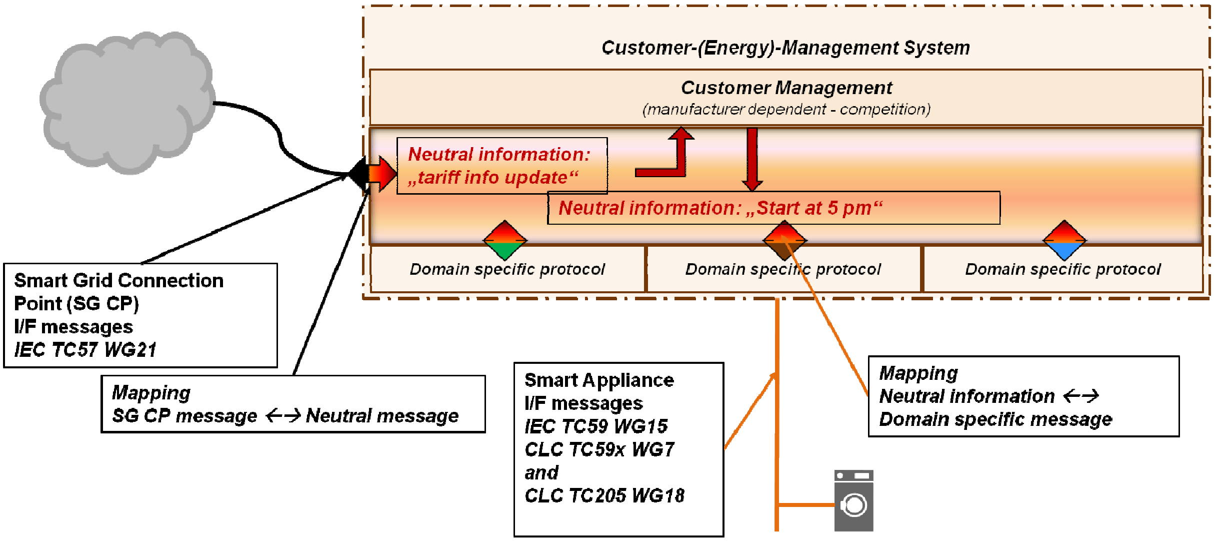

Figure 12: Interfaces of the Common Architecture Model and the responsible standardization bodies, [1], [7], [8].

Next to international official standardization, Consortia and Alliances are also working on parts of Smart Home standardization fields. Their intention may be different, e.g. defining own alliance related industry standards like AllSeen or the target of the EEBus Initiative to support international standardization bodies like IEC/TC 57, CLC/TC 205 and IEC/TC 59.

Figure 13 lists alliances and initiatives working on in-home solutions where as figure 14 lists alliances and initiatives working on cloud related solutions.

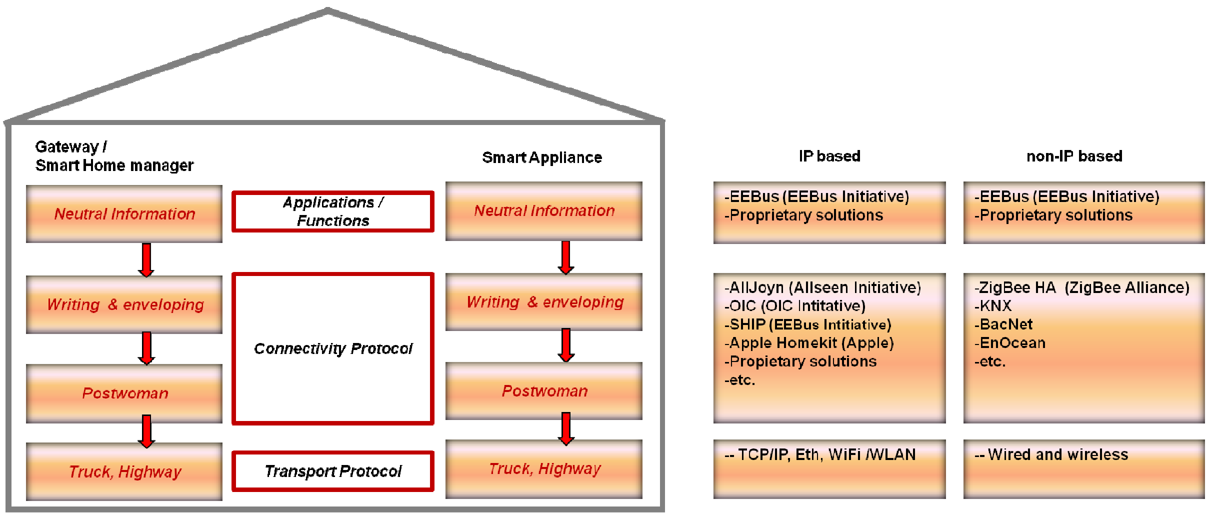

Figure 13: Consortia and alliances working on in-home solutions, [7], [8].

Note: This is only an overview and does not imply to be complete.

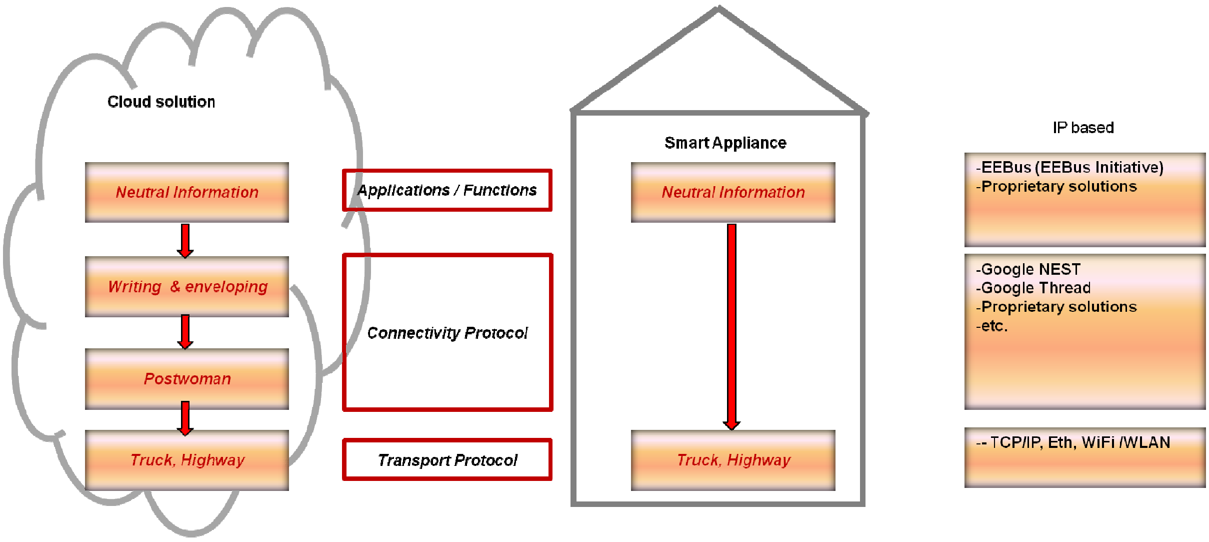

Figure 14: Consortia and alliances working on cloud solutions, [7], [8].

Note: This is only an overview and does not imply to be complete.

The next figure lists alliances and consortia which are working and may have an influence on future Smart Home solutions.

Note: this list is not complete and does not have any prioritization.

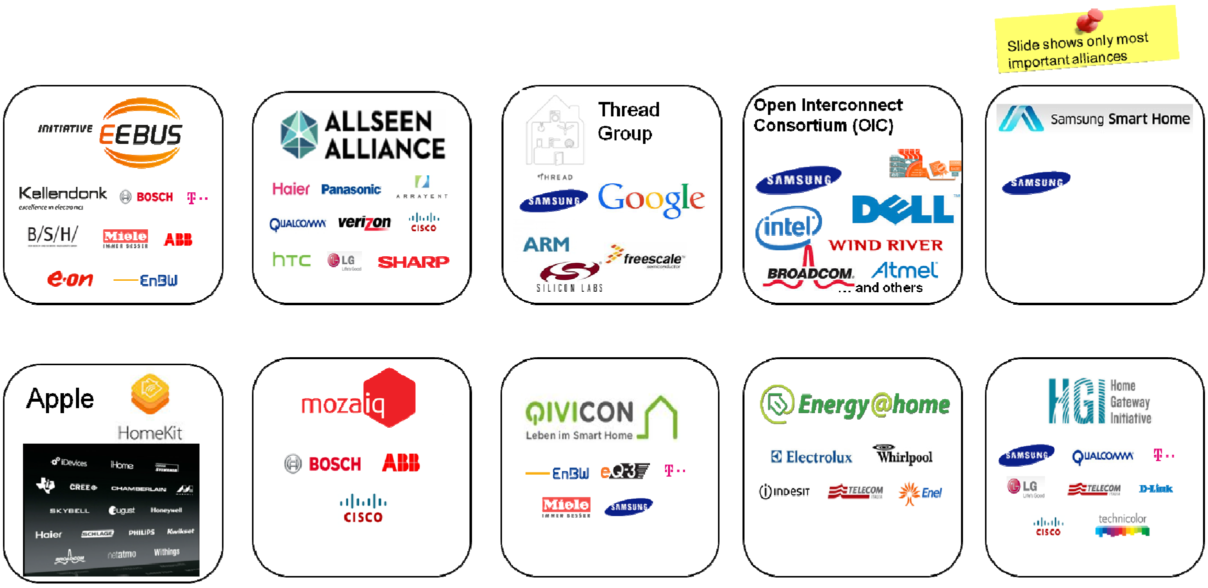

Figure 15: Consortia and Alliances with possible impact on European Smart Home solutions, [7], [8].

Next steps

As stated at the very beginning the success of Smart Home solutions is very much related to the capability of being interoperable. This defines the possible footprint of such solutions.

Interoperability can be achieved by

- creating the market by dominance (e.g. Apple) or by
- defining and developing interoperable solutions (e.g. Industry and/or public standard), accepted by many manufacturers.

As one of these Industry and Public Standard examples, a couple of European manufacturers, being member of the three initiatives Agora, France, EEBus Initiative, Germany and Energy@Home, Italy, decided to align the Common Data Models of the main energy related use cases. This is in line with the European Commission and their projects

- DG Connect project “Common Ontology”
- DG Energy “Ecodesign Preparatory Study on Smart Appliances”.

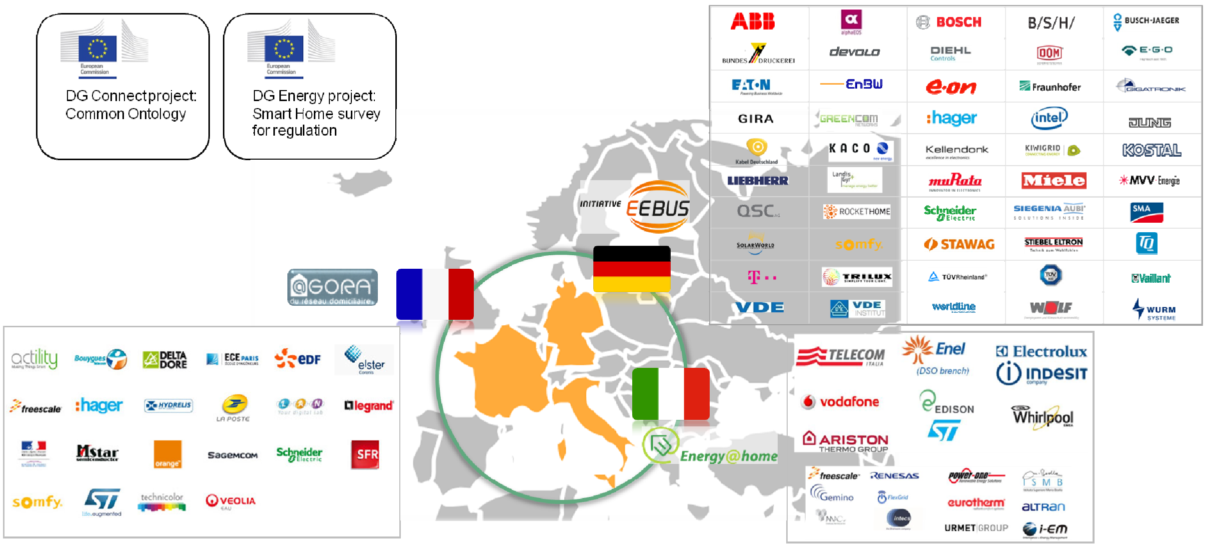

Figure 16: Agora, EEBus and Energy@Home Initiative “Alignment of Common Data Models”, [7], [8].

The outcome of this project will become part of Public Standards like CENELEC TC 59X/WG 07 (prEN50631-x, Smart Appliances).

This approach hopefully enables manufacturers to realize Smart Appliances supporting defined interoperable solutions and to give the customer the freedom to select his own device from his preferred manufacturer.

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Sustainable Processes
First Set of Standards
Smart Grid Reference Architecture
CEN-CENELEC-ETSI Joint Working Group Report 2014:
Extended Set of Standards support Smart Grids deployment
Overview Methodology
General Market Market Model Development
Smart Grid Architecture Model User Manual
Flexibility Management
Smart Grid Interoperability
Smart Grid Information Security

More information available at:
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Too smart for our own good: Why intelligent appliances seem as far away as ever

George Wilkenfeld[1] and Lloyd Harrington[2]

[1]George Wilkenfeld and Associates, [2]Energy Efficient Strategies

Abstract

There is no limit to the promises made about ‘smart’ appliances, but what has been delivered so far is disappointing. While the web, smart phones and screens have gone from strength to strength, we have had not much more than the ‘internet refrigerator’ (launched four times, failed commercially twice). There is confusion (among manufacturers as well as consumers) between the information which enables smartness and the appliance which delivers the actual energy service. The appliances themselves deliver services in much the same way as they always have because the basic physical needs for heat, cold, light and power have not changed. but smartness provides ways of optimizing the delivery of these services.

“Smartness” offers way to optimise delivery of these service, provide that smart appliances can straddle the old world of power grids, wires, cautious engineering and standards, and the new wireless world of internet, data and rapid innovation. That gap has not yet been bridged.

This paper identifies the main problems holding back the market for appliances, which increase human welfare and optimise energy and resource consumption in an intelligent way. The great historical success of household appliances has been their ability to simplify complicated tasks (e.g. wash and dry clothes in one continuous operation) and elaborate what was formerly limited (e.g. the vast range of specialised heat and power applications in the average kitchen). The current directions of appliance ‘smartness’ – too often trying to achieve relatively simple objectives in unnecessarily complicated ways – runs counter to this historical trend.

The paper review the types of services that manufacturers are presently offering in the products they call smart. It concludes that most are of marginal value to the individual consumer, to society as a whole and to the environment, and carry new risks which are often unrecognised. It proposes criteria for assessing ‘useful smartness’ (or ‘intelligence’) in appliances and proposes strategies for how this might be attained.

1. Who needs a smart refrigerator?

The refrigerator is the perfect appliance. It does one essential thing reliably and well. Keeping perishable food and drinks at safe storage temperatures, it is the terminus of the ‘cold chain’ that links farms to factories to ships to supermarkets to homes, and delivers perishable and frozen food cheaply and safely to virtually every electrified home in the developed world.

It is also the poster child for energy efficiency. Nearly every energy labelling and minimum energy performance standards (MEPS) program has started out with refrigerators [1]. Under the influence of these policies, the energy-efficiency of refrigerators worldwide has increased spectacularly, at the same time as their average size and features have increased and real prices have fallen [2]. The gains for other products have not been as great, partly because no other efficiency programs have been in place as long, and partly because the refrigerators of the 1970s and 1980s offered a bounty of low-hanging fruit in their vast scope to improve insulation, compressors, refrigerants and controls.

How then can we improve on the refrigerator, and in particular make it “smart”? The first attempt was made by Electrolux, with its 1999 announcement of the “Screenfridge” [3], although the actual honours for first on the market may belong to LG’s “Internet Digital DIOS” refrigerator, first available in mid 2000.[4] Both Electrolux and LG claimed that their product was “smart” because it had an LCD [liquid crystal display] touch screen, the ability to connect to the internet via a home area network (assuming the home had internet access, which was then rare), and a number of novel functions:

- messaging functions, to take account of the fact that household members frequently passed through the kitchen, and often left notes to each other on counters, notice boards, or fixed to the metal surface of the refrigerator with fridge magnets;

- screen-based entertainment functions, to replace the small television set that was becoming common on kitchen counters; and

- functions related to the primary purpose of the kitchen, i.e. food storage and preparation: recipe access and filing, grocery item inventory and ordering functions. However, the inventory function relied on user discipline to manually enter contents on the screen, scan barcodes or electronic tags on food packaging (not always present on fruit and vegetables, let alone cooked meals and leftovers!).

Needless to say, none of these made the slightest impression on the market, and the first coming of the “internet refrigerator” was considered a commercial flop.[5] However, the experience was not all wasted. Here is a contemporary description of the LG Internet Digital DIOS:

> “The new device has a 15.1-in TFT [thin-film-transistor] LCD screen and LAN [local area network] port and supports video telephony and a Web camera, enabling users to take photos and send video messages. They can also watch TV and exchange E-mail. It has a simplified graphic user interface designed for use by housewives who are not familiar with Internet technology. Other features include short message writing with an electronic pen, scheduling programs, voice messaging, touch screen and music box.”[4]

This sounds uncannily like the smart phone except for the screen size, and even there the smart phone is catching up. The internet refrigerator anticipated the consumer (as distinct from business market) smart phone user interface by about 7 years: Apple launched its first iPhone in June 2007.[6]

In fact, the original internet refrigerators have now come back in slightly different forms. The Electrolux “Infinity I-Kitchen refrigerator” was re-launched in Brazil in 2010, this time with an invitation to software and application (“app”) writers to take advantage of its potential.[7] In 2012 LG re-launched its internet refrigerator, this time along with clothes washers and ovens that could be connected to home Wi-Fi routers.[8] After 15 years, the appliance industry is still looking for a market for the smart refrigerator.

2. The smart phone as the new universal remote

The resurrection of the internet refrigerator has taught one vital lesson - that the primary user interface is no longer the screen on the refrigerator (although a small screen is still present), but the smart phone. All of the LG devices launched in 2012 can be accessed by smart phone apps, which send alerts to both the user (“door open”) and the manufacturer (“service required”) and allow the user to interrogate the appliance (“is wash finished yet?”) and adjust settings remotely.

The smart phone has become the default remote control, even for appliances that never had one before. Appliances such as televisions and air conditioners have had wireless line-of-sight remote controls since the mid 1950s.[9] Once electronic audio and video entertainment products proliferated in the living room, it became a problem to keep track of their various remote controls. There was briefly a market for a “universal remote” that could learn and could mimic the functions of the many separate remotes.

In the end however, the holy grail of remotes has come from an unexpected angle – the smart phone. Several air conditioner manufacturers (including Samsung, LG, Panasonic and Daikin) offer products with Wi-Fi connection to the internet, and apps dowloadable to a smart phone that can mimic remote control functions. Daikin, for one, has the option of a direct Wi-Fi link from the smart phone to the air-conditioner when an internet connection is not available.[10] In effect, this would turn the smart phone back into a local remote control, albeit with a somewhat longer range than the old infra-red line of sight.

Alas, each manufacturer has a separate operating system, so householders with more than one brand of product in their home will need more than one app. Most manufacturers are trying to lock consumers into their own systems, by offering several appliances that can be operated from a common proprietary platform. GE, for example, is offering a range of W-Fi connected ovens, refrigerators, dishwashers, clothes washers, tumble dryers and water heaters, each paired with an app.[11] However, the alerts and settings appear to be much the same as the user would have access to if they were at the appliance – whether they are willing to pay for the ability to do so without leaving the couch or when out of the house remains to be seen.[1]

Many people are familiar with expression "if all you have is a hammer, everything looks like a nail".[2] To a smart phone, everything looks like it needs an app. However, very few of these applications has actually enhanced the basic energy-efficiency or functionality of the appliances concerned – their ability to cool, cook, heat and wash – and has, in many cases, created a new set of problems.

3. Grid-Interactive Smartness

The most promising areas of appliance smartness are those which automatically interact with the electricity grid and minimise, rather than maximise the need and the temptation for users to interact. Such appliances respond to information about the grid by modifying, delaying or in some cases initiating operation. The relevant grid information may be transmitted by way of time-variable price data or signals indicating network congestion or the availability of renewable energy sources, for example. The appliances could be pre-programmed to respond to specific parameters, e.g. "start wash cycle when supplied energy price is below a preset threshold" or "start when my photovoltaic output is approaching daily peak".

Alternatively, appliances could be set to respond to commands from an agent authorised by the user, such as an energy supplier or a demand response aggregator. The agent would monitor the condition of the grid, decide on the optimum collective – as distinct from individual – action and send demand response signals to the appliances. The type of response would depend on the wishes of the user and the smart capabilities of the appliance. During peak load events, refrigerators may delay defrost or allow compartment temperature to drift up to preset limits, and air conditioners might increase their thermostat set point or constrain their operating power. Electric water heaters may temporarily increase their heat storage capacity, and turn on their elements (or heat pump motors) during periods of excess renewable generation.

In fact, once these demand response capabilities are built into appliances, consumers may have the choice of controlling them through their own software and contracting with energy suppliers to deliver an agreed quantum of load reduction by programming and prioritising appliances as they wish. If they get tired of the responsibility, they can transfer control to an authorised agent without changing their appliances.

Products with these capabilities are already on the market.[12] In the USA, there are many thousands of whole-house air conditioner installations with programmable communicating thermostats, which can adjust temperature when called on by the utility. In Japan and Australia, there are hundreds of models of split unit air conditioner with built-in hardware and software interfaces for gird interactivity. In the USA, Energy Star has set standards for "connectedness" for refrigerators and clothes dryers.[3]

The value of grid-interactive smartness derives from the economics of power supply. For example, a network operator with access to a large stock of demand responsive appliances can delay supply extensions and upgrades, provided that the load response is controllable, predictable and reliable.

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[1] Some of secondary functions – such as the ability to adjust water heater temperatures or alerts regarding chilled water filter replacement – may be more accessible and effective though apps than through on-appliance settings and alerts.

[2] Variously attributed to the psychologist A.Maslow (1966) or the psychologist A.Kaplan (1964). http://en.wikipedia.org/wiki/Law_of_the_instrument

[3] At the time of writing only 11 of the 955 refrigerators listed as Energy Star compliant met the "connected" criteria – 8 from Samsung and 3 form LG. No clothes dryer models met the connected criteria. http://www.energystar.gov/productfinder/product/certified-residential-refrigerators/results

Relying on user response to price signals, even if notified a day in advance, is much less reliable than contracts which allow the authorised agent to send commands directly.[4]

Of course, users will want some incentive to enter such an arrangement. This may be in the form of up-front payments for purchasing and connecting appliances with the necessary capabilities, annual incentives, payments per load modification event or simply protection from high-price periods if the user is on a time-of-use tariff.

This model of appliance smartness is the opposite of what the appliance industry has tried so far:

- Products with grid-interactive capabilities are generally indistinguishable in appearance and function from conventional modern appliances, whereas the "smart refrigerator" introduced in 2000, for example, made a feature of visible evidence of smartness such as touch screens;
- The value to both users and remote agents is in "setting and forgetting", rather than constant interaction via smart phone. This does not mean that the user loses authority and autonomy, but it is exercised in different ways – by choosing, or not, to buy a grid-interactive appliance and activate its capabilities, by choosing to freely enter or leave a demand response contract (subject to whatever conditions, rewards and penalties it contains) and – if the contract permits – opting out of some demand response events;
- The value relies on the active participation of a third party – an energy supplier or aggregator – and cannot be realised solely by and shared between the manufacturer and the user, as is the case with other novel smart features.

This conflicts with the general tendency to equate smartness with unfettered user autonomy, constant remote interaction between user and appliance, novel functions and the promise of greater independence from "old-style" commercial actors such as electricity suppliers. Indeed, companies from the information technology and communications (ICT) sectors have begun to enter the traditional appliance market by promising to make appliances more like smart phones. They do not always seem to appreciate that appliances have a long history of development and refinement, and – unlike smart phones – are meant to last for more than a decade rather than a year or two, and are only useful while connected to the electricity grid and drawing relatively large amounts of power at voltages that are dangerous to the user.

Of course, selective applications of ICT can greatly enhance the social utility of the household appliance stock. The management of local home energy networks as well as the entire grid will be enhanced if appliance operation is co-ordinated in some way, whether this control is embodied in distributed software or the more traditional forms of centralised grid management. Even so, not much ICT is needed. Most of the economic benefits can be realised through relatively simple one-way signaling, to a relatively small group of high-power appliances.[14].

4. Some emerging problems

Smartness, in whatever form, is usually presented positively by manufacturers and in the popular press, as a sign of continuing progress in the development of appliances and lighting. However, the risks and dangers are rarely mentioned.

Safety and risk

A user who turns on an appliance manually is able to see and assess any obvious dangers. A remote "on" signal may appear to be risky, but for most appliances it is not. After all, timers and delayed start functions have been common for decades. Appliances have long been designed to start, operate and stop safely when unattended – even those that undertake discrete cycles, such as ovens or clothes

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[4] A recent Belgian study of dynamic electricity pricing, the "Linear" project, reported "Reacting manually on the time-varying prices clearly required too much effort, and the users in this group gave up quite quickly. However, the automatic responding people perceived the Linear system as without any loss of comfort and their consumption was often shifted from the early evening to later at night." http://spintelligentpublishing.com/Digital/Metering-International/issue1-2015/index.html

washers. Modern products will not start unless the doors are closed, and in some cases will sense if there is no load (whether food, clothes or dishes).

On the other hand, the smart phone creates the risk of the user intervening in ways that are not useful – e.g. delaying and interrupting operation or changing settings without being fully aware of the condition of the appliance and its load. The capabilities of smart products can actually lead to risky behaviour, not least with regard to food safety. In 2014 Grundig's UK marketing manager observed:

> "There is a lot of talk about connecting appliances to consumers through their smartphones and computers. It is clear that connected appliances are the future but the execution needs to be right. For instance, you might be able to turn on your oven from the comfort of your office, but is it a good idea to leave a raw chicken in the oven the whole day?" [13]

In some cases the risks of smart operation are apparent to the user, and can be addressed. For example, constraining the operating power of air conditioners during peak load events will obviously allow the temperature of air conditioned space to rise beyond what it would otherwise be. If the load reduction is co-ordinated, then the impacts can be distributed across all participating consumers so everyone still gets some cooling during an event, while the integrity of the grid is maintained – which also benefits non-participants because, after all, if there are blackouts nobody gets any cooling.

Nevertheless, households that are unwilling to participate, possibly because they have members who are very old, very young or ill, can opt out of demand response entirely by not purchasing smart air conditioners, choosing not to activate smart capabilities, or opting out occasionally by exercising over-rides. Thus they can choose to forego some or all of the incentives and benefits available to full participants. Alternatively, if given advance notice, participants could undertake pre-cooling and use the thermal mass of their dwellings to dampen the temperature rise during demand response events.

Other consequences of smart operation are less obvious. Refrigerators and freezers could respond to grid problems by suspending compressor cycles for a period. Such response should no doubt be subject to an internal assessment of temperatures by the appliance itself to ensure that they stay within the design range for each compartment. The response period should end once internal temperatures drift to the top of the permitted range.

Effectively, the refrigerator contents would be used as a store of cold to defer compressor operation for short periods when emergency response is required from the grid. With greater notice of a supply side constraint a smart refrigerator-freezer could deliver a greater response; the freezer compartment could be super-cooled beforehand and internal controls could transfer cold from the freezer to maintain acceptable fresh good temperatures for several hours without compressor operation. Separate freezers have considerably more flexibility in operation than products with fresh food compartment because of the narrow temperature constraints for perishable fresh food.

Smart, grid responsive refrigerators can be developed, but it would require changes to the way the product currently operates and controls its internal temperatures. For the product to continue to deliver a high quality energy service (in this case, storage of perishable foods) it must have the autonomy to control itself within its own design parameters, while responding as much as it can to the external request for energy reductions. If this is mishandled then, unlike the air conditioner example the effects and risks – in this case higher rates of food spoilage – are not immediately apparent.

Security and Privacy

Most types of smartness introduce new security and privacy risks for the user. These include the risks that unauthorised parties could gain control over the appliances, or that unauthorised parties (or even authorised parties) could monitor appliance use for purposes ranging from the criminal (robbing vacant homes) to the annoying (marketing).

Any method of appliance communications and control that involves the internet is liable to the same vulnerabilities as any other internet transaction. Appliance software and Wi-Fi routers can be hacked, and smart phones can be lost. Manufacturers are aware of these risks, but rarely mention them. GE Appliances, to its credit, has a page on "Connected Home Security" which reads like a basic course in internet hygiene, offering hints such as this:

"Loss of your Smart Phone and Tablet. Call the GE Appliances Connected Home Help Desk as soon as possible if your lost or stolen smart phone has a GE Connected Appliances app installed. GE Appliances can disable outside-of-home control of your appliances. If you cannot reach the GE Appliances Connected Home Help Desk immediately, please contact your smart phone provider to notify them of you lost device." [15]

If the user contracts the smart operation of the appliance to an authorised agent such as a utility, security tends to be higher, because the communications pathways are inherently more secure (e.g. powerline carrier signals, mesh radio) or – if via internet protocol – more strongly encrypted.

The interest of some manufacturers in communicating with smart appliances may be more for their own commercial interest than the user's. Certainly, connected appliances offer the benefits of remote status monitoring and fault diagnosis, and the opportunity to update software (analogous to automatic updates for the operating systems of smart phones or perhaps electric cars). The collection of operating data without user identification is also a rich resource for research on customer usage and for the design of new products. However, data collection from identified users holds the risks of intrusive marketing of goods and services at the very least, and at worst, surveillance for more sinister purposes. In fact, given the data security risks there may be a good market for smart appliances that are *not* capable of two-way communication.

Information overload and complexity

The unspoken assumption behind ICT is that there is no such thing as too much information, provided it is efficiently managed and presented in a useful way. This principle may not yet have found its way into smart appliance design. True smartness makes the user's life simpler rather than more complex. A 2014 review in WIRED magazine observed:

"The common approach to smart appliances has been to simply add features, the more the better. We see this all the time on TVs, bundled with clunky YouTube browsers and half-baked media players. Washing machines are not immune to this feature-stuffing phenomenon…

Berg, a design and technology development startup in London, shares this wariness of a mindlessly connected future, and much of its work centers on envisioning a smarter way forward. That said, the studio's latest project might be even crazier than an internet-connected washing machine. It's an internet-connected washing machine that makes perfect sense.

It reminds us that connectivity doesn't always need to introduce complexity.

The prototype, Cloudwash, shows how technology can be harnessed to make simple, sensible improvements to unglamorous appliances. It features a streamlined user interface; wash options are reduced to just a few frequently-used presets, with plain language labels like "sports clothes" or "everyday wash." A second knob lets you schedule loads not by starting time but, ingeniously, ending time. Other features let you order detergent from Amazon with the press of a button. The machine communicates seamlessly with a smartphone app, though it doesn't make you use it if you don't want to."[16]

Of course, such research may be more useful if applied directly to the on-board controls of the clothes washer itself rather than as an app that tries to correct for poor design. In this regard the models of appliance smartness and ICT smartness have something in common. The smart phone app is intended as a trial for features that enhance the capabilities of the basic operating software, and if popular enough may be incorporated into the next update. However, it would be unfortunate if the market for smart appliance apps was driven by the need to correct failures in basic usability and design, rather than to add functions that are worthwhile on their own.

Energy consumption

Smartness is generally thought to make appliances more energy-efficient, but this is not necessarily so. Conventional appliances have increased significantly in energy-efficiency over the past thirty or forty years, due to better designs and materials and the introduction of electronic controls and solid state technologies such as LEDs. All this has been accomplished without invoking "smartness".

Energy-efficiency should continue to progress under pressure of government policies, rising energy prices and consumer expectations. Of course, energy consumption may still increase if product size or capacity increases, and new functions are added, faster than the rate of efficiency improvement.

Some forms of smartness might increase operational energy-efficiency further by monitoring usage patterns for example and automatically modifying settings to reduce cycle times or minimise unwanted heat loss or gain. However, the potential energy gains are probably marginal compared with what has been and can still be achieved through good product design and engineering. Every appliance can and should be designed to be energy-efficient whether it is smart or not and whatever its user settings.

One area where smart appliances could reduce energy waste is through co-ordination within clusters of devices with related functions. If they can monitor the state of other devices in the cluster they can power manage themselves to the lowest possible state. For example, a set top box and a game console can assume they are not required if the screen to which they are connected is off and there is no other video streaming requirement, and can put themselves into sleep mode even if a badly behaved user leaves them on. This is most applicable to home entertainment and information technology clusters, but could be extended to any situation where appliances operate in tandem to supply energy services. However, it is arguable that the same objective can be achieved in much simpler ways, by power boards with standby power controllers.[5]

Many aspects of smart performance can increases rather than decrease energy use. Shifting time of use does not on its own increase energy efficiency, even if it reduces average energy price to the consumer. In fact, overall primary energy efficiency may be lowered if load is moved into overnight periods when coal-fired power stations, which are hard to turn down, provide all or most of supply. Energy-efficiency may also be compromised at the point of end use. Interrupting the operation of a clothes washer, for example, may mean that the wash water cools and has to be reheated, or perhaps the detergent loses some of its effectiveness. After the interruption, extra operations may be needed to get the wash load to the required standard of cleanliness and dryness by the target cycle completion time.

Smart pre-cooling of freezers to lower temperatures in advance of demand response periods significantly reduces the efficiency of the refrigeration system operation and increases heat gain into the low temperature compartment. Smartness in this case reduces operating efficiency, but this is acceptable if it is only activated for short periods and/or when the need is anticipated.

Finally, the communications aspects of smartness can introduce new loads which, though small, individually may be multiplied across many products. Building a Wi-Fi or other wireless capability into an appliance, for example, adds a new standby energy load. One critical aspect is to ensure that any network connection is appropriate for the task. Most smart connections will require only a few bytes of information to be exchanged on an irregular basis. Therefore very low bandwidth network options, which also have very low power requirements, are generally the most suitable. Power consumed by network connections increases exponentially with bandwidth. The elements of the communications system needed to access the appliance may add further loads, unless pre-existing systems such as the internet and Wi-Fi are used. In some cases there may be some compensating reductions in load, as when smart phone apps substitute for remote controls and eliminate the energy required to support the remote control sensors on the appliances. On balance however, smartness is just as likely to increase energy consumption as to reduce it.

5. Intelligent Appliances

This brief survey suggests that there is scope for building and selling what might be called “intelligent” as distinct from “smart” appliances. The characteristics of such appliances would be:

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[5] Differentiating intended device inactivity (when viewers watch a long program without adjusting any settings) from unintended (leaving the screen on after going to bed) is difficult, whatever the technology. The Australian state of Victoria’s Energy Efficiency Target (VEET) scheme found that some standby power controllers defaulted to switch power off to the peripherals if the controller does not detect a change in volume or channel after a pre-set time period.[17] Needless to say, this led to many users discarding the product.

- They focus on their primary function, rather than add on novel features which complicate user control, usability and program or cycle selection;
- They have built in energy-efficiency and low energy consumption (not the same things);
- They are usefully and selectively smart, in ways that create genuine and lasting value, not just novelty (although some innovation and experimentation is necessary for progress);
- They acknowledge, address and help the user manage additional risks or dangers;
- They use information and communications technology in ways that are of value to the user but do not overload the user; and
- They recognise the role of energy utilities and other intermediaries in the delivery of energy services, but do not mandate or preclude any particular business or contractual relationships.

In many respects, the long-established principles of simplicity, conservatism and reliability that have underpinned the electric power supply industry for over a century make a more promising platform for appliance intelligence than the rapid change, novelty and obsolescence which may be said to mark the rise of the ICT sector in the past three decades. Ultimately, appliances deliver energy services, not communications services.

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Energy Efficient Appliances for Low-Income Households

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Abstract

The EU Directive on energy labelling of household appliances (Directive 92/75/EC) and its revision (Directive 2010/30/EU) are quite successful in helping households choose energy efficient products (http://www.measures-odyssee-mure.eu/public/mure_pdf/household/EU12.PDF) and in motivating the industry to invest in energy efficient product design. Purchasing energy efficient appliances is, however, dependent on financial capacity, as energy efficient appliances are still expensive. Low-income households very often use second-hand appliances which are old and less efficient which implies a high potential for energy savings. So, the above mentioned directive is only one factor in the expansion of the energy efficient appliance market, bringing the products into households.

Another factor is the introduction of policy programmes which support the investment in energy efficient appliances. In the context of a research project, the framework of conditions for such a programme for low-income households has been identified. First of all, it was examined which household appliance could most effectively be funded. It turned out that a replacement programme for refrigerators is the most promising. The supporting and inhibiting factors which influence the acceptance and the success of a replacement programme for refrigerators for low-income households were identified. For the analysis the existing international policy programmes which aimed at low-income households were screened and insights from group discussions with the target group and with stakeholders such as manufacturers and municipals were gained. We concluded that the funding of a replacement for an appliance alone does not guarantee the saving of energy; some boundary conditions also have to be considered.

Introduction

A low income in conjunction with the use of old and energy inefficient appliances can quickly lead to energy poverty, particularly if energy prices are high. A possibility of counteracting such a development is to help low-income households to invest in energy efficient appliances. This has the dual benefit of providing a financial saving for the household as well as a carbon reduction potential for the environment. Low-income households, however, have a double disadvantage in their lack of knowledge in saving energy in everyday life [1], and their financial constraints in converting energy saving tips into an investment of, for example, energy efficient appliances. Measures which consider both aspects could therefore help low-income households to reduce energy costs. There is a financial motive to save energy in order to save money.

The reduction of energy consumption, by the promotion of energy efficient appliances, is one aim of EU members at least since the energy efficient directive in 2007 was developed. The EU Directive 92/75/EC and its revision 2010/30/EU is only one measure applied in order to achieve this. Policy programmes and directives at the EU, and national levels support this. Examples include: Directive 2012/27/EU on the obligation to precisely label electric appliances (energy classes G-A^{+++}); Ecodesign directive 2009/125/EC which prescribes the eco-friendly and therefore for example energy efficient design for energy related products; and the European Ecolabel for appliances that have a reduced environmental impact throughout their life cycle, from the extraction of raw material through to production, use and disposal. There is also the well established Energy Star label set by the U.S. Environmental Protection Agency for appliances that meet strict energy efficiency criteria.

Table 1 displays the up-to-date maximum energy efficient classes of the EU label and the minimum requirements by the Ecodesign Directive for Appliances. The standby losses have also been successfully reduced through regulatory instruments (EG 1275/2008).

Table 1 Energy Efficiency Standards for Appliances

Appliance	Highest energy efficiency grades of the EU energy label	Minimum standards according to the ecodesign directive for energy related devices
Washing maschine	A+++	A+
Tumble dryer	A [A+++]	C
Dishwasher	A+++	A+
Cooling and Freezing Equipment (e.g. refrigerators)	A+++	A+
Electric Ovens	A	-
Vacuum cleaners	A	G
fume extraction hood	A	G
Lamps/light bulbs	A++	A/C
TVs	A+	D

Source: www.eu-label.de, www.eup-network.de, www.dena.de

Appliances in low-income households

In order to decide whether a certain appliance is to be funded, the energy efficiency potential of the appliance needs to be considered together with the ability to furnish low-income households with the appliance.

Electricity consumption of appliances

The comparison of electric appliances shows that refrigerators (with an integrated freezer) consume almost 25 % of the electricity in a household (Figure 1). They are the most energy intense appliance followed by TVs, cookers and dishwashers. The consumption of electricity largely depends on the length of time the appliance is in use. As refrigerators are continuously in use all day long, they consume a lot of energy and there is a high energy saving potential. A trend has, however, been observed for a longer daily use of TVs, computers and DVD-players [2] [3].

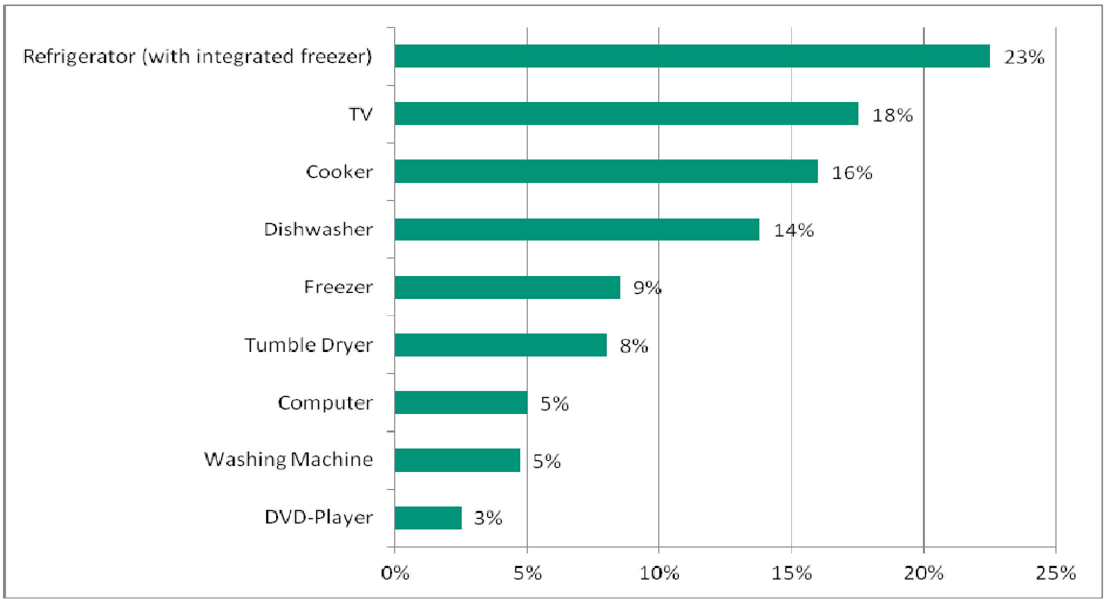


Figure 1 Electricity consumption of electric appliances in private households [4]

The absolute energy consumption of an appliance is influenced by further factors such as energy efficiency class, age of the appliance, service life, size, technical state of an appliance and consumer behaviour (e.g. refrigerator: temperature set, defrosting periods, time left open). A change in the behaviour of the consumer can lead to certain energy savings [5] [1].

Regarding service life, information and communication technologies (ICT) have an especially short life time (about 8 years compared to 15 years for white goods) because of the fast technological development and the consumers' ambition always to have the latest product. Furthermore, energy efficiency is not a significant purchase decision factor for these appliances. For example, for TVs the screen size is important and this is in turn correlated to electricity consumption [6:28]. PCs need much more energy than laptops [7] which could be a reason for funding laptops if most of the low-income households use a computer.

Penetration of appliances in low-income households

The following Figure 2 shows how many low-income households in Germany (so called "Hartz-IV households") utilise at least one of the appliances listed. Most of the households have acquired refrigerators and TVs as well as washing machines, but just 65 % use a computer. The study did not investigate the use of a cooker but this was analysed by Schlomann and colleagues [8:69] who found that 89 % of the German households have a cooker, which is usually electric [9:21]. The same study determined that some of the low-income households actually have more than one TV and more than one refrigerator [9].

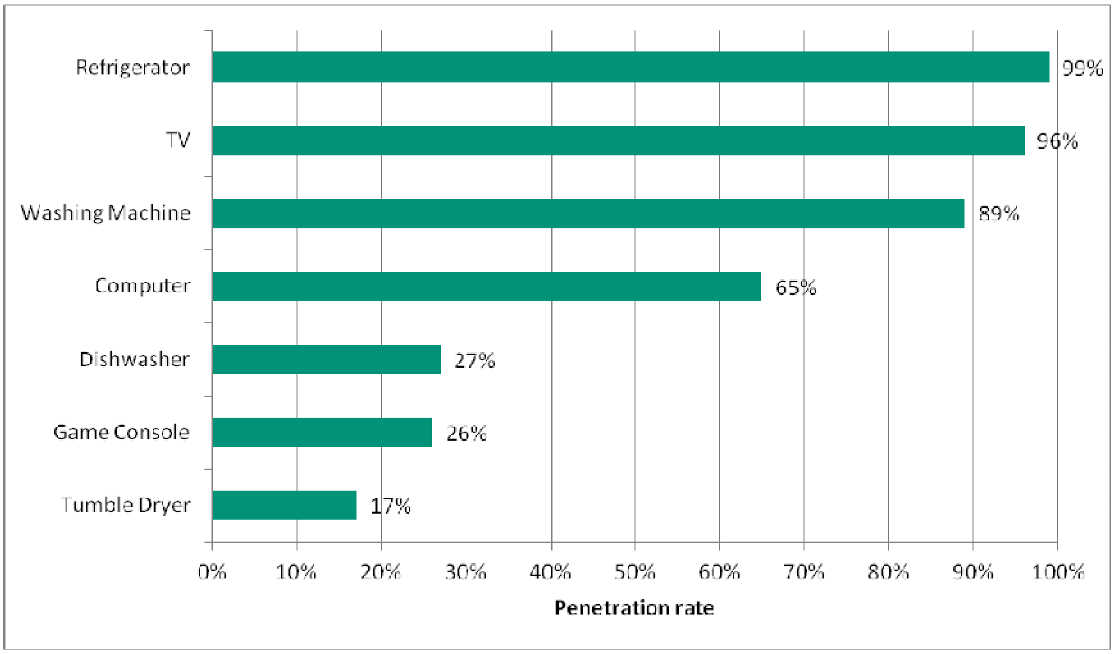


Figure 2 Furnishing of low-income households in Germany (Hartz-IV) with appliances [10]

Low investment energy saving devices could also contribute to energy saving: Switchable power strips are useful to reduce the stand-by losses of electricity, which are especially high for information and communication technologies (ICT). It is sometimes possible to use timers to switch off unused energy related appliances. Thermometers for the fridge can help to set a minimum temperature which is not too low and the use of electric kettles rather than boiling water on the cooker also saves energy. Such low investment measures have an immediate effect without changing behaviour on a big scale. The use of these small devices can also lead to an improved energy perception and could have an effect on other fields of consuming energy [11].

Refrigerators are most promising

As one could see above refrigerators have got a high electricity consumption and are widespread throughout low-income households. Additionally low-income households very often use second-hand appliances which are obsolete and not energy efficient. There is substantial potential for *saving energy* from changing refrigerators that are more than ten years old, with high energy consumption, to new energy efficient refrigerators (Figure 3).

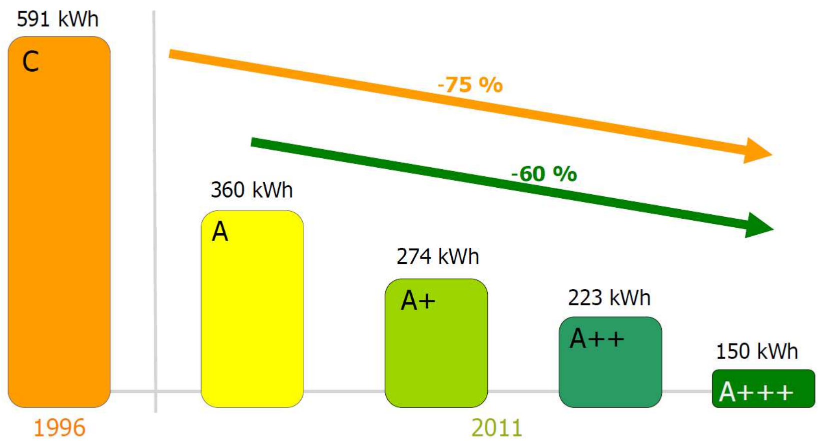


Figure 3 Comparison of Refrigerators with integrated freezers of different energy classes [12]

Some other factors besides energy saving confirm refrigerators as most promising for a policy programme for energy efficiency for low-income households. A high energy costs saving potential gives rise to a relatively low *amortisation rate* of the initial cost. Amortisation rate is displayed as:

$$\text{Amortisation rate} = \frac{\text{investment for new appliance}}{\text{annual energy savings (kWh) * energy costs per kWh}}$$

The older and the more energy intensive a refrigerator is and the lower the energy demand of its replacement, the shorter the amortisation rate. The best amortisation rate can be identified when a refrigerator and a freezer are substituted by a fridge-freezer: about 6 years amortisation rate without funding (Table 2).

Table 2 Amortisation rate of different scenarios

scenario	**annual energy savings**	**energy costs**	**investment costs**	**amortisation rate**
substitution of a ten year old fridge by a A++ fridge	200 kWh	25 ct/kWh	500 Euro	10 years
substitution of a ten year old fridge by a A++ fridge with 200 Euro subsidy	200 kWh	25 ct/kWh	500 Euro	6 years
substitution of a ten year old fridge and a ten year old freezer by a A++ fridge-freezer	300 kWh	25 ct/kWh	500 Euro	6 years

Source: Assumptions based on [13]

Another factor is the *ecological payback period* demonstrated by carrying out a life cycle assessment. The carbon emissions during the usage of refrigerators exceed the emissions during production [12] to make it worthwhile replacing a ten year old fridge with a new A^{++} fridge after four years usage [14].

The *Product Carbon Footprint (PCF)* is the CO_2 balance of raw materials production, appliance production, trading, utilisation, transport and recycling. Bosch und Siemens Hausgeräte GmbH [12] report that 90% of the environmental effects of an appliance account for utilisation, 1% for transport and waste disposal each as well as 8% for production. Of course this depends on the appliance in consideration.

To account for *environmental costs* one has to look at saved emissions (CO_2 equivalents) by a refrigerator replacement. The assumption of 585,5 g CO_2/kWh (German energy mix 2005) and 70 €/t CO_2 environmental costs [15] [16] [17] as well as annual energy savings of 200 kWh per household leads to annual savings of CO_2 equivalents of 117 kg, and 8,19 € savings of environmental costs per household.

All in all the funding of the refrigerator, together with small energy saving devices such as switchable power strips, is the most promising way to support low-income households to save energy because of the following criteria:

- High penetration of refrigerators in low-income households
- High penetration of very old refrigerators in low-income households
- Refrigerators are not primarily a prestige object like a TV
- High energy saving potential of refrigerators
- Relatively low amortisation rate of refrigerators
- Quick payback of refrigerators regarding carbon emissions during production
- Substantial environmental cost savings

In order to ensure an energy-saving effect within a replacement program, the sponsor has to restrict the *size* and energy consumption of the new appliance. Moreover, the consumption patterns should be checked for rebound effects (i.e. proof of adequate disposal and no longer use of the old appliance). For a campaign, an additional information sheet regarding the correct temperature and the right placement of a fridge (e.g. not beside the cooker) is important.

International overview of policies

Valuable insights can be gained from existing international projects which address low-income households and energy efficiency. Examples from Australia, Austria and Germany are described below. Programmes in Denmark, Italy, Switzerland, Spain, Netherlands, USA, Canada and Cuba are also mentioned and used to discuss the drivers and barriers for a refrigerator replacement programme.

Australia: Energy Efficiency Program for Low-income Households (2003-2006)

Low-income households in South Australia receive free home energy checks which aim to examine household energy saving potentials in the following areas: water heaters, fridges and freezers, heaters and air-conditioners, washing machines, lights, cookers, and other appliances. An energy Advisor comes into the households and can help the householder to understand their energy bills and how to read their electricity meter. The participating households are also offered a free retrofit kit and may choose to receive a $50 payment for retiring their second (or third) fridge or freezer. They could also be eligible for an interest free loan to purchase a new energy efficient appliance or other energy saving items. This offer is only available if significant energy savings, through replacement of a fridge or washing machine etc., are identified during the home energy check. A basic indicator of qualification for this scheme is the eligibility of at least one member of the household for a Health Care Card. This measure is organised by South Australian Government's Energy Efficiency Program for Low-Income Households in collaboration with six community based welfare organisations.

The programme was successful in reducing energy costs of the participants [18]. However, since a central contact address was missing and the programme was not intensively promoted, the target group was not sufficiently reached. Additionally the administrative barriers for the loan were very high.

Austria: Energy Consultancy and Refrigerator Replacement Programme (2009-2010) and the Separation Bonus Programme ("Trennungsprämie" 2009-2010)

Free energy consultancies were offered in different projects [19], and old refrigerators replaced with new energy saving devices. Additionally, new cookers, washing machines and boilers were funded. The new appliances were delivered directly into the households without cost and the old ones were properly recycled. Low-income household who had long-term problems paying their electricity bill, and were at risk of their power being cut-off were eligible for aid. In every project just one specific model of refrigerator was offered which lead to a low take-up.

In another programme, the "separation bonus" was available for the whole population regardless of income [20]. A subsidy of €50 or €100 was provided for the purchase of A^{++} rated refrigerators, A rated Washing machines and A rated tumble-dryers from a pre-defined list. Information material for retailers was provided to support the promotion of energy efficient appliances. This programme had such a good take-up that the budget ran out ahead of time.

Germany: Electricity Saving-Check programme ("Stromspar-Check" since 2008) and a contracting programme (since 2012)

In Germany there has been a nation-wide *Electricity Saving-Check programme*[1] [21] since 2008, which helps low-income households save energy, with several low-cost measures. It is organised by the German Caritas Association and the Association of Energy Agencies in Germany (eaD e. V.) and financed by the national Climate Initiative of the German Federal Ministry of Environment. Low-income households receive an electricity saving consultancy at home which is executed by specifically trained long-term unemployed people. The first step is to check the electricity demand of a household and provide well-directed recommendations for electricity saving. The households also receive a package of small energy saving devices such as switchable power strips and energy-saving light bulbs. The household can additionally receive a €150 voucher to buy an A^{+++} refrigerator if: 1) the old one is at least ten years old, 2) the fridge replacement saves a minimum 200kWh per year (quantified by a 48-hour measurement of status quo), 3) the old fridge is verifiably recycled and 4) the new one has a similar capacity to the old one. The whole programme is free of charge for the households and evaluated by monitoring. It is available in more than 100 German communities. The Caritas Association employs the consultants and contacts the households supported by 17 regional energy agencies and a handbook for the implementation of energy saving advice for low-income households is provided. The programme has a high media profile and the trained consultants are very motivated.

Even with a €150 voucher an A^{+++} refrigerator is expensive, so the consumer advice centre and the municipal energy supplier in Wuppertal provide low-income households (recipients of social transfers, retired persons, students) with a selected A^{++} refrigerator for a low monthly instalment[2]. The precondition is a need assessment and the household has to self-finance the fridge, supported by payment by instalments (a kind of a contracting model) with a subsidy of €50. The selected appliance is chosen for the needs of single parents and retired persons. This is the weak point of the programme, however, as the focus on one particular appliance does not fit every low-income household. For example, families with many children would have problems using this programme.

Other exemplary campaigns, targeted at all households were run in:

- Denmark – campaigns on A to A++ rated cold appliances, Danish Electricity Saving Trust, 1999-2008 [22]
- Italy – Tax allowance on A+ or A++ rated refrigerators, since 2007
- Switzerland – Funding of A+++ rated cold appliances, top-ten-programme, 1997-2015
- Spain – Funding of A to A++ rated appliances, 2005-2012

[1] http://www.stromspar-check.de/willkommen/ (11.12.2014)

[2] http://www.wsw-online.de/unternehmen/artikel/detail/kampf-gegen-energiearmut-wuppertaler-kuehlschrank-austausch-vorbild-fuer-europa/ [15.12.2014]

- Netherlands – Energy Premium Scheme for domestic appliances, 2000-2003USA – Appliance Rebate Program Helping low-income homeowners, 2011-2012; Habitat for Humanit Refrigerator Replacement Program, ongoing [23]
- Canada – The Refrigerator Replacement for Low-Income Households Program, 2014-2015 (a Hydro-Québec initiative run by MARCON)
- Cuba – Funding of appliance replacement for a low monthly instalment, since 2005

Success factors of policy programmes

As indicated in the international overview, there are barriers and drivers of policy programmes for low-income households. The impact of a funding programme particularly depends on inhibiting and supporting factors which motivate the target group making use of the financial support. Politics should account for drivers and find answers to barriers.

Schönherr and colleagues [24] analysed several policy measures for sustainable consumption to identify these inhibiting and supporting factors. The factors are related on the one hand to the consumers (level of information, individual characteristics, social environment and financial constraints) and on the other hand to the market structure and political framework [25:145f]. Additional insights came from the group discussion with the target group.

The assumed policy measure behind the analysis of barriers and drivers is a refrigerator replacement programme for low income households which combines a subsidy for a new energy efficient appliance with a credit to pay the rest.

Supporting factors

The interest and use of a funding measure depends on individual and contextual factors. These have an impact on the perception of the measure and on the decision behaviour. The following Table 3 shows the supporting factors and implications for a successful policy measure for low-income households promoting energy efficient refrigerators.

It can be seen that the target group might have a great interest in a funding measure of energy efficient refrigerators and the measure might be successful. Existing factors (public discussion) and structures (market development) can be used and intensified.

Table 3 Supporting factors and implications of a policy measure promoting energy efficient refrigerators for low-income households

Supporting factor	Description	Implication
Individual Characteristics		
Level of information	The subject of energy efficiency has a high public profile and matters for the consumer.	The measure should make use of the public discussion.
Motivation to save energy	Due to financial constraints most of the target group are motivated to save energy and see need for action.[3]	The measure should utilise the motivated people and use them as propagators to communicate the measure.
Low budget	High energy costs make the funding of energy efficiency and energy saving measures attractive. This is especially the case for low-income households.	Focus of the measure should be the contribution to lower energy costs.
Social Structure		
Word-of-mouth	Parts of the target group use public meeting places and communicate profitable campaigns to others.	A standardised programme eases the inter-regional perception.
Market Structure		
Market for energy efficient appliances	The market for refrigerators is mainly focused on energy efficient appliances and the EU-directive obliges traders to label the energy class of appliances. This leads to a high market transparency.	The neccessary infrastructure exists and could be further supported with the measure. This information has to be accessible, credible and understandable.
Political Framework		
Synergies	There often exist other sunstainable policy programmes. Interactions of measures lead to a mixing of messages. Policy measures should be synchronised regarding aims, regulations, formal conduct, communication and marketing.	Synergies should be used, and double funding of investments should be prevented.[4].

[3] [10:12], [11], result of the group discussion with the target group.
[4] [26:39]

Inhibiting factors

Even when the target group has a certain motivation making a claim on the funding there are some individual and contextual factors which could prevent this. Identifying these barriers and their solutions can prevent a failure of the measure. Table 4 gives an overview.

It becomes clear that knowledge gaps as well as financial constraints have to be overcome. An effective marketing concept for a political measure is therefore indispensable.

Table 4 Inhibiting factors and implications of a policy measure promoting energy efficient refrigerators for low-income households

Inhibiting factors	Description	Implication
Individual Characteristics		
Level of information	Knowledge gaps regarding energy saving potentials of appliances have been identified in several studies.[5] In particular, the target group does not recognise action possibilities.[6]	Information on energy saving potentials needs to be provided.
Tendency for withdrawal	A complex and bureaucratic process of application can frighten the (often poorly educated) target group.	Involvement of stakeholders who are in contact with the target group (e.g. social workers), and can support them with their application.
Low motivation	Some of the target group are not motivated to engage with any topic and are not interested in energy saving.[5]	For them financial incentives and a regional reference is important.
Purchasing routines	Consumers have different preferences as to where and how to buy goods.	Give the consumers as many choices as possible.
Credit limit	High investment costs could be a barrier.[7] Low-income households with debts are unable to obtain loans.	The funding has to be sufficient and to be combined with a contracting model or an interest free loan. A^{++} appliances are usually more favourable than A^{+++} appliances.
Transport	The target group could have difficulties transporting the new refrigerator and disposing of the old one.	Usually the retailer takes care of the delivery and disposal. This is important information for the target group. Possible costs should be funded.

[5] [10], [27].
[6] [10], [11], result of the group discussion with the target group.
[7] [11]

Inhibiting factors	Description	Implication
Social Structure		
Heterogeneity	Different needs and behaviours exist within the target group.[8]	There is a necessity to address the target groups in different ways (e.g. via different social organisations).
Prestige objects	Refrigerators are usually for everyday use and not considered prestige objects. When they are used as a prestige object there is a trend for big American style refrigerators.	Restrictions regarding the size of the refrigerator are necessary.
Market Structure		
Market development	The state of the art techniques and energy saving possibilities are permanently changing.	The measure has to be flexible especially when it is long-term (e.g. top ten lists have to be updated all the time).
Political Framework		
Top-down vs. bottom-up	A change of mind cannot be reached just through political measures (top down). It also needs motivated consumers (bottom-up).	Intrinsic motivation may not be replaced by extrinsic motivation. This suggests that the funding should not be too high.

Policy recommendations

It can be seen that the funding of a replacement of an appliance alone does not guarantee the saving of energy; some boundary conditions have to be addressed. The combination of 1) meaningful preconditions 2) subsidies 3) payment in instalments 4) energy saving tips and handling instructions and 5) information material for retailers and sellers appear to be the most promising.

This was tried in a German project in 2008 [9] which was quite successful but was only implemented in a small region. The project “implementation of energy efficient measures in Hartz-IV households” („Umsetzung von Energieeffizienzmaßnahmen in Hartz-IV-Haushalten“) was a German study commissioned by the Federal Ministry of Environment. Every one of the above named conditions was considered. The 108 participating households received social benefit but the electricity contingent provided was insufficient. Every household received a free energy check at home and several energy devices. An economic efficiency calculation regarding the investment in a new refrigerator was conducted and if the result was promising the household received a coupon of €200 or €300 (depending on household/refrigerator size). This coupon was directly applied to the purchase at participating retailers. In addition, the households were offered a micro-loan with instalments no higher than energy costs saved each month (a kind of a mini contracting).

Challenges with addressing low-income households

Regarding the financial strain of energy costs and possible options for action, the low-income households seem to be homogeneous. A closer look however, reveals the different demographic

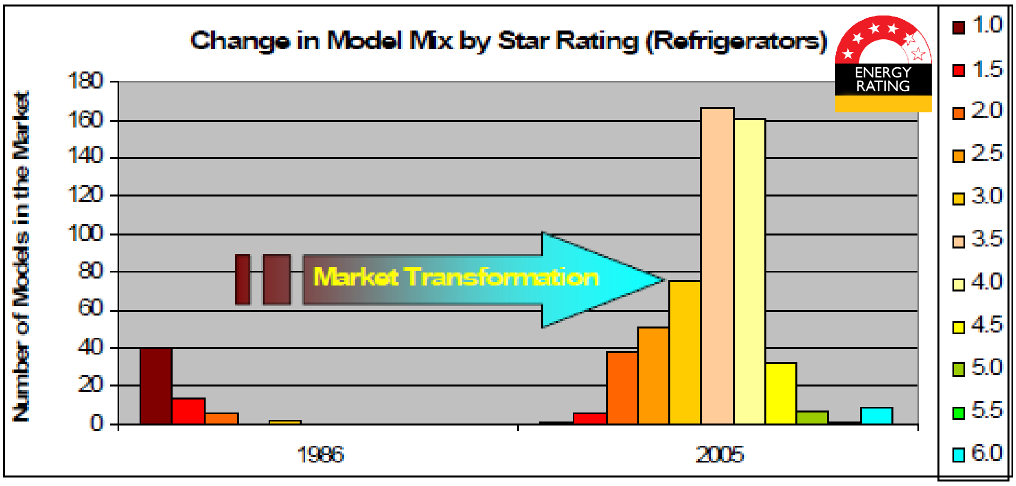
[8] [19]; [10] [28]

characteristics and the different motivation of the target group regarding environmental matters. There is thus a special challenge to define the target group and communication of the funding programme.

The most comfortable definition of low-income households is the EU-standard: people with an income lower than 60 % of the mean equivalent income of the country. The verification of household income is a very extensive task however, and another option for defining those eligible for subsidies has to be found. In Germany the most practicable solution is to use the “Sozialpass”. This is a document for people in a social pre-care position and is used for example for discounts of museum fees.

Conclusion and Outlook

A policy programme for refrigerators for low-income households not only supports the household but also contributes to the development and diffusion of energy efficient appliances. The energy market share of efficient appliances is increasing over time and this process could be reinforced by political action. Figure 4 shows the increasing number of energy efficient (high energy star rating) refrigerators and freezers as an impact of the labelling and Minimum Energy Performance Standards (MEPS) policies. If retailers, consumers and politics are all inspired, energy consumption can be reduced and the climate protected.



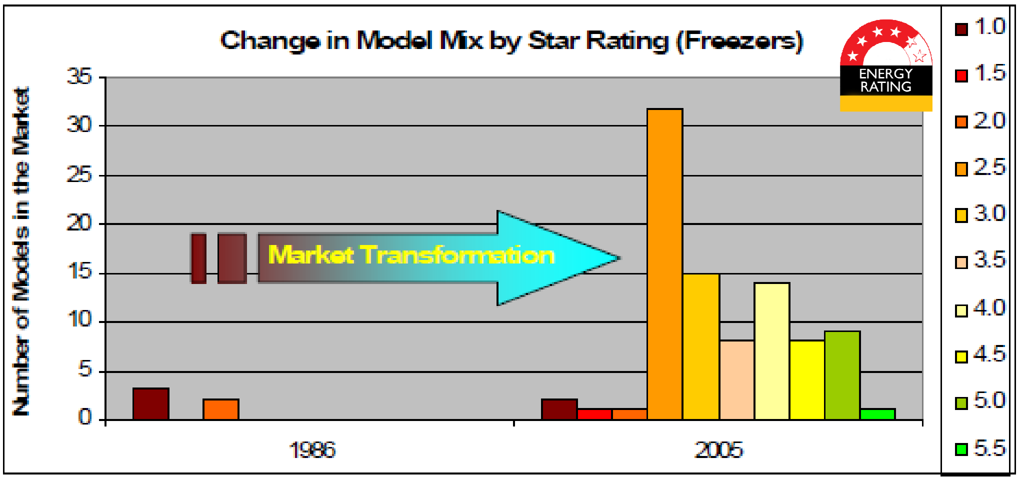


Figure 4 Illustration of Refrigerator and Freezer Market Transformation in Australia between the years 1986 and 2005 comparing number of models by star rating (the higher the more efficient) available in this years [29:44f]

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Market Transformation through Emerging Technology: Lessons learned from the introduction of hybrid heat pump clothes dryers into the North America market

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Abstract

The North American market for clothes dryers is undergoing a transformation towards higher efficiency driven by a combination of improved technology, financial incentives, and product labeling. In 2014 and 2015, three major appliance manufacturers have introduced the first hybrid heat pump electric dryers into the North American market, for the first time offering American consumers a 35-50% more energy efficient option improvement in energy efficiency over the standard electric dryer. In addition, the U.S. federal government's ENERGY STAR program has introduced energy efficiency labeling for dryers in the U.S. for the first time. These developments are due in part to the efforts of utility energy efficiency program providers in the US working together through the Super-Efficient Dryer Initiative (SEDI). SEDI was created in 2008 to accelerate the market introduction of highly efficient dryers into the U.S. and Canada, building off of the successful market introduction of heat pump dryers in Europe.

This paper will provide an overview of the development of a North American market for energy efficient dryers and compare how it has been both similar and different from the European experience. In addition, this paper will discuss important lessons learned that are applicable more broadly to market transformation and emerging technology in an international context. Finally, the paper will provide insights from the SEDI experience on a range of topics including: research needs, financial and policy mechanisms to support market introduction, and the importance of productive engagement between stakeholders.

Background

Clothes dryers are one of the largest end uses of household energy in the United States (US). The average dryer consumes 769 kWh of electricity per year, less than water heating and space conditioning, but more than any other household appliance including refrigerators (Environmental Protection Agency, 2014). For decades, North American dryers had shown little to no improvement in energy efficiency due to a lack of technological innovation, minimum energy performance standards (MEPS) which were set in 1991 and never updated, and the absence of attention from efficiency labeling programs like ENERGY STAR. Since the most recent EEDAL conference in 2013, this situation has changed dramatically with the implementation of the first ENERGY STAR label for dryers, the revision of the U.S. federal test procedure for dryers and the establishment of a revised MEPS, and the introduction of three dryers which use heat pump technology into the US market.

This recent, rapid development in North America was preceded, and encouraged, by a similar transformation in Europe. The first heat pump dryer was introduced there in 1998. Since entering the European market, heat pump dryers have experienced steady market growth, continued efficiency improvements, and decreased costs; for more information on the market transformation of heat pump dryers in Europe, please a sister paper authored by Eric Bush[1]. Inspired by the European experience, the

[1] "Heat Pump Tumble Dryers: Market Development in Europe and MEPS in Switzerland", EEDAL 2015

Super-Efficient Dryer Initiative (SEDI) was created in 2009 by the Vermont Energy Investment Corporation (VEIC), Grasteu Associates, and the Collaborative Labeling and Appliance Standards Program (CLASP) to coordinate and focus the efforts of U.S. and Canadian utility energy efficiency program providers, policy makers, and manufacturers in order to develop a North American market for energy efficient dryers.

In the fourth quarter of 2014, appliance manufacturers LG and Whirlpool introduced hybrid heat pump dryers to the North American market; marking the culmination of efforts by the ENERGY STAR program, utility energy efficiency program providers, major appliance manufacturers, and SEDI. These new dryers are now available online and in stores through several major North American retailers. At US $1,500 and $1,900, the prices of the new hybrid heat pump dryers are higher than the standard electric dryer sold in North American; which sells for less than US $700. US energy efficiency program providers have begun to provide financial incentives to support the market introduction of these products by reducing the price to consumers, but sales remain low. In March of 2015, European manufacturer introduced under the Blomberg brand a version of a heat pump dryer model already popular in Europe at a price of US $1,600. We expect several additional utility energy efficiency program providers to offer financial incentives. These events represent the start of a significant transformation in the efficiency of the North American dryer market.

Building a Market for Heat Pump Dryers

A comparison of the development of the European and North American markets for energy efficient dryers offers a unique opportunity to observe the interaction of product labeling schemes with consumer financial incentives in order to develop a market for a new highly efficient appliance. This comparison is still very much unfolding as the European market matures and the North American market begins to form, but there are already some interesting insights that can be gained.

Product Labeling

The European dryer market has benefited from a comprehensive mandatory “comparative”[2] product labeling scheme that has included an aspirational top performance tier used to drive efficiency improvements. In 1995, the European Commission implemented the first energy label for dryers. At the time, they had set the highest performance level, the “A” tier, at a level products currently sold on the market could not achieve. This aspirational tier, along with financial incentives, motivated manufacturers to introduce new heat pump drying technology into the European market. Initially, heat pump dryers carried a hefty price premium over the standard European dryer, which utilized electric resistance condensation technology. Since market introduction, European heat pump dryer prices have come down and efficiency has improved; as a result, heat pump dryers achieved 40% market share sixteen years after market introduction.

Unlike the European labeling scheme, the ENERGY STAR labeling program is a voluntary “endorsement”[3] product labeling scheme. The ENERGY STAR label only appears on those products which meet the ENERGY STAR efficiency requirements. The ENERGY STAR program introduced the ENERGY STAR for Clothes Dryers label in 2014 to recognize dryers that use about 20% less energy than the North American standard vented resistance electric dryer. Since the summer of 2014, dryers have been eligible to qualify for the new label. As of this writing, 57 models of electric resistance (and 14 natural gas fired) dryers have been qualified to carry the ENERGY STAR label in the U.S. and Canada. An important distinction between the European and ENERGY STAR labeling scheme is that, unlike the European labeling scheme, ENERGY STAR does not support a future, aspirational tier to motivate market introduction of new highly efficient technologies.

[2] Standards & Labeling Guidebook, CLASP, 2014, pg 9
[3] Ibid. CLASP

Figure 1: LG Ecohybrid

The ENERGY STAR program has recognized this limitation and used a different but related program, the 2014 ENERGY STAR Emerging Technology Award: Advanced Clothes Dryers, to establish an aspirational efficiency tier for dryers utilizing new highly efficient technologies. The award recognizes electric dryers that offer energy savings of approximately 40% (using the most efficient cycle option) compared to the standard electric dryer sold in the U.S. (Environmental Protection Agency, 2015). The dryers are featured on the ENERGY STAR website, and manufacturers can indicate that their dryer has received the award in advertisements. As of June, 2015 three clothes dryers which utilize heat pump technology have received this award.

The LG EcoHybrid Heat Pump Dryer (model DLHX4072) is a vented, full size (0.18 cubic meter capacity[4]) dryer utilizing hybrid heat pump and supplementary electric resistant heating to dry clothing. According to the manufacturer, the dryer uses 53% less energy in its most efficient mode compared to the US MEPS (10 CFR 430.32(h)) (LG Electronics, 2015). The same dryer also sells at the retailer Sears under their house brand name as the Kenmore Elite Advanced Hybrid Dry Technology Electric Dryer with Steam (model 81593).

Figure 2: Whirlpool Hybridcare

The Whirlpool HybridCare Heat Pump Dryer (model WED99HED) is an unvented (condensing) full size (0.18 meter capacity) dryer utilizing hybrid heat pump and supplementary electric resistant heating to dry clothing. According to the manufacturer, the dryer uses 73% less energy in its most efficient mode compared to pre-2004 traditional North American electric dryers when the dryer is paired with a matching washer (Whirlpool, 2015).

Figure 3: Blomberg DHP 24412W

The Blomberg DHP 24412 is an unvented (condensing) dryer which has the smaller footprint typical of European dryers, but a rated capacity comparable to full-size North American dryers. Testing by NEEA suggests that this may be the most efficient clothes dryer currently available on the North American market.

Unfortunately, the 2014 ENERGY STAR Emerging Technology Award: Advanced Clothes Dryers (ETA) program does not provide a seamless connection with the ENERGY STAR for Clothes Dryers label. First, the ETA program does not have a label, and manufacturers are not permitted to put anything directly on their products indicating that they have received the award. ETA graphics are restricted to point of purchase displays, web pages, and/or promotional materials.[5] Second, the LG, Whirlpool and Blomberg dryers are the only three models that have received the ETA award. These three dryers have also qualified for the ENERGY STAR for Clothes Dryers label, but nothing on the product packaging tells consumers that these three models are more efficient

[4] US and Canadian dryer capacity is rated in volume of laundry, rather than weight. Although physically smaller, European dryers are often rated to dry larger loads of laundry.

[5] 2014 ENERGY STAR Emerging Technology Award Graphic Guidelines http://www.energystar.gov/sites/default/files/eta_graphic_guidelines.pdf

than the other 67 dryer models which may now carry the ENERGY STAR for Clothes Dryers label. Perhaps more importantly, the ETA program only lasts for a limited amount of time. EPA is no longer accepting applications to the ETA program for new dryers, although new dryers can register under the less stringent ENERGY STAR for Clothes Dryers label. At the time of writing this paper, there are no plans to continue the ETA program beyond 2015. When the ETA program expires at the end of 2015, utility energy efficiency program providers in North America must find a new way to identify and promote highly efficient dryers.

In response to the current regulatory environment, the Northwest Energy Efficiency Alliance (NEEA), SEDI, and several California electric utilities have joined together to develop an independent specification for highly efficient clothes dryers. The specification will be designed to address several aspects of dryer performance, including energy efficiency and drying time (NEEA, 2014). The Consortium for Energy Efficiency (CEE) is a nonprofit focused on accelerating the uptake of energy efficient products in the US and Canada. The CEE Super-Efficient Home Appliances (SEHA) Initiative has developed advanced performance tiers for other appliances in the past, and may choose to develop advanced tiers for clothes dryers as well. A CEE SEHA advanced tier for clothes dryers could replace the ETA program as the mechanism for identifying and promoting highly efficient dryers North America.

Financial Incentives

There are further similarities between the market introduction of heat pump dryers in Europe and North America. Both regions offer a patchwork of financial incentives for the purchase of energy efficient appliances, although US incentive programs have traditionally covered a broader range of products and have been accessible to a greater percentage of consumers. In Europe, a limited number of cities (e.g. Zurich and Bremen) offer incentives for dryers that qualify for the highest efficiency “A” tier under the EU Energy Label. In the US, some energy efficiency programs offer incentives for ENERGY STAR for Clothes Dryers label and a smaller number of programs offer incentives for the dryers that have received the ETA program award.

At the time of writing this paper, 68 US state and regional energy efficiency programs offer consumers financial incentives ranging from $25 to $150 US dollars per unit for clothes dryers that carry the ENERGY STAR label (Environmental Protection Agency, 2015). So far, seven North American energy efficiency programs offer financial incentives for dryers that receive the ETA program award (Environmental Protection Agency, 2015) as shown in Table 1. These programs also typically provide advertising in order to increase public awareness. In 2015, we expect several additional energy efficiency programs to join this list.

Table 1: Energy Efficiency Program Providers offering incentives

Program Name:	**Dryer Rebate**:
District of Columbia Sustainable Energy Utility	$400
Efficiency Vermont	$400
New Jersey’s Clean Energy Program	$300
PSEG Long Island	$300
Sacramento Municipal Utility District	$300
Energize Connecticut	$200
Silicon Valley Power, City of Santa Clara	$100

Revised Test Procedure

In North America, advocates for more efficient clothes dryers faced a particular challenge in the form of an outdated test procedure. As late as 2013 the clothes dryer energy consumption test procedure defined by the U.S. Department of Energy was not sophisticated enough to distinguish variations in energy efficiency between modern clothes dryers; as a result, the ENERGY STAR program was able to develop neither the ENERGY STAR for Clothes Dryers label nor the ETA program. In order for these schemes to move forward it was necessary to first update the US federal test procedure.

The energy efficiency of a clothes dryer is heavily dependent both upon how efficiently it is able to remove water from laundry, and also how well it is able to avoid over-drying (continuation of the drying cycle after the laundry is dry). Over-drying has been identified as a significant source of wasted energy in baseline US clothes dryers. The original U.S. federal test procedure was designed before the broad availability of sensors that measure the remaining moisture content of laundry. These sensors, at least theoretically, have the ability to reduce the tendency of dryers to over dry laundry.

By 2013, several dryers sold on the US market were equipped with moisture sensors and promised the ability to appropriately terminate the drying cycle and avoid overdrying. However, testing the ability of dryers to automatically terminate the cycle is important, because prior research has shown that there are significant differences in how well moisture sensors work in different dryers. Improving this function is a major opportunity for dryer energy efficiency, offering a 10-15% efficiency improvement to baseline dryer technology by eliminating unnecessary over-drying (Horowitz, Denkenberger, Mau, Calwell, & Wanless, 2009).

North American stakeholders, including utility energy efficiency program providers coordinating through SEDI, worked with the US federal government to revise the federal test procedure for dryers. In January 2015, a new federal test procedure came into force, but in an unprecedented move the US Department of Energy allowed manufacturers to choose between two test procedures, one that continues to ignore cycle termination, and one that includes cycle termination. Normally, the ENERGY STAR program uses the test procedures that DOE develops, but in this case the Environmental Protection Agency, which administers ENERGY STAR, determined that it would only accept results from the test procedure that includes cycle termination. This unfortunate situation has resulted in uncertainty for all stakeholders. In November 2014, the Department of Energy initiated a new rulemaking process to revise the current test procedure. We expect DOE to set a new test procedure and minimum standard in 2017, which would then enter into force in 2022.

The SEDI Coalition

SEDI used the dryers' opportunity as a call to action for energy efficiency programs to provide coordinated early market support and significant financial incentives for energy efficient dryers. At the time this paper was written, SEDI's coalition includes 15 utilities and two regional organizations, the Northeast Energy Efficiency Partnerships (NEEP) and the Northwest Energy Efficiency Alliance (NEEA). These sponsors fund SEDI's activities and participate in SEDI's working groups. Combined SEDI sponsors represent over 64 million residential electric and gas customers and have roughly 600 million US dollars available for domestic energy efficiency programs. This scale provides dryer manufacturers with the confidence that there will be meaningful financial support when they bring efficient dryers to the North American market.

Energy efficiency programs require rigorous technical verification of energy efficiency savings to justify the inclusion of clothes dryers in financial incentive programs. SEDI has worked to identify, prioritize, and coordinate the research that allows energy efficiency programs to support new products. SEDI working groups have produced:

- Research plans prioritizing research activities based on their importance to developing financial incentive programs;
- A field research protocol to guide clothes dryer field research that would be conducted by several organizations across North America;
- A laboratory test methodology that more accurately resembles real world drying conditions; and,
- Performance specification for highly efficient driers that will ensure significant energy savings.

Conclusions and Lessons Learned

It is clear that a combination of labeling schemes and financial incentives have been instrumental in creating markets for heat pump clothes dryers in Europe and the US. Furthermore, an aspirational performance tier has been important in both regions in motivating manufacturers to develop products with greater efficiency. Finally, both regions benefited from organizations which helped identify and resolve obstacles to market transformation: SEDI in North America, and TopTen in Europe.

Even though this emerging technology initiative is specific to the US and Canada, there are a couple of lesson learned that can be applied to a broader context; specifically, the importance of building upon past successes and the importance of careful timing.

Build On Past Success

Although the US and Canada lack the coordinated momentum towards defined future energy efficiency levels provided by the European Energy label, the combination of the ENERGY STAR label and energy efficiency program financial incentives have become a potent force in the North American domestic appliance market. Years of energy efficiency program incentives have successfully grown U.S. markets for ENERGY STAR qualified appliances. The promise of access to the ENERGY STAR label and significant retail incentives are now sufficient to motivate manufacturers to invest in research and development of new technologies.

A global perspective also allows for the identification of shared emerging technology challenges at the regional and national level, and the facilitation of discussion towards solutions. An integrated perspective for an emerging technology program can reduce duplication of efforts, enable rigorous and streamlined vetting of technologies, and promote valuable knowledge sharing between utilities, governments, and other emerging technology stakeholders on successes elsewhere. To date, SEDI is one of the few US initiatives to have integrated international best practices into its program design and market approach.

Choose Timing Carefully

Realistically, there is little that emerging technology programs can do to change the underlying dynamics faced by industry, utilities, and regulators in a particular market. Assuming that these dynamics are sufficiently aligned, timing becomes important. For example, a large, unexploited savings opportunity that can be obtained with a high degree of certainty at a reasonable cost will naturally tend to receive a significant portion of a program’s budget (CFLs being the obvious example).

SEDI emerged at a time when US and Canadian energy efficiency program managers needed to bring new technologies into their portfolios because they foresaw that they would not be able to continue meeting their energy savings goals by simply promoting large volumes of CFLs. Had SEDI started five years earlier, it might not have been successful because at that time these program managers had not yet developed a strong interest in finding such new technologies. SEDI also launched at about the same time that Asian washer and dryer manufacturers started to have a significant presence in major U.S. retailers, creating pressure on U.S. manufacturers to fight for market share by introducing new products. Finally, SEDI has effectively leveraged the success of the European TopTen initiative and the European Energy Label in building a European market for efficient clothes dryers. That success, even though in a substantially different market, has helped reduce the perception of risk of pursuing emerging clothes dryer technology in North America.

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Heating, Cooling and Water Heating

Water Heater Technical Study to improve MEPS - South Africa

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Abstract

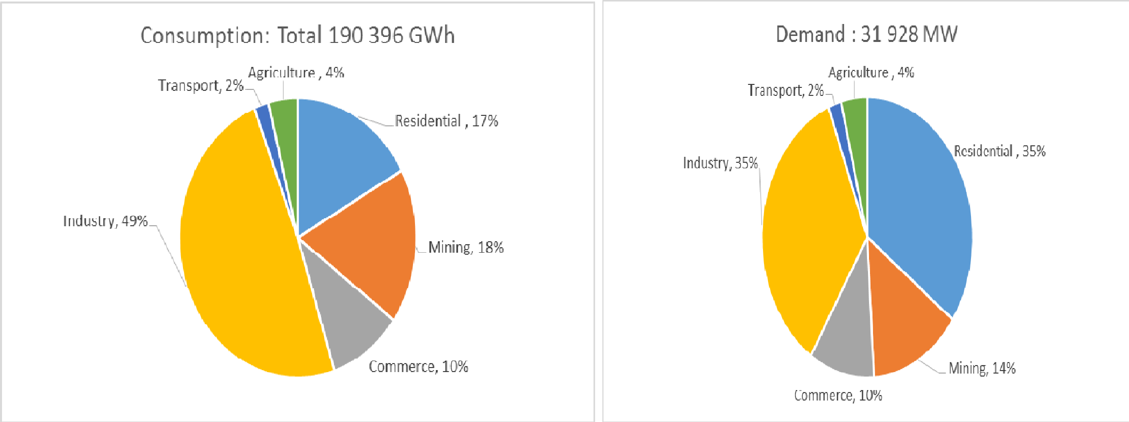
The residential sector accounts for approximately 17% of electricity use in South Africa, but as much as 35% during peak periods. Within households the electric water heater (WH), commonly referred to as a geyser in South Africa, is responsible for between 40-50% of total consumption and contributes substantially to morning and evening peaks. Although there is an existing Minimum Energy Performance Standard (MEPS) regulated by the standing heat loss test (SANS151) it was formulated many years ago and has not been improved since its introduction. In the current context it is considered low and ineffective.

Numerous attempts to improve the MEPS have proved futile primarily due to strong resistance from the industry. The Super-Efficient Equipment and Appliance Deployment (SEAD) is supporting the South African Government in implementing its Standards & Labeling (S&L) programme for residential appliances, which includes WH. In an attempt to break this 'deadlock' a cost efficiency technical study on WH was commissioned by SEAD. The research would use global and local industry experts using to conduct the research so as to provide credible empirical data to clarify cost-effectiveness issues and allow for informed decision making.

Introduction

South Africa's electricity crisis has worsened since the country experienced large scale rolling blackouts in 2008 due to supply shortages. Two mega coal generation plants, with a combined generation capacity of 9,600 MW, which were expected to start delivering power in stages starting January 2010 are still under construction in February 2015. The delay has forced the national utility (Eskom) to run its existing power stations harder and to delay essential maintenance work. The consequence five years later is an increase in plant accidents and failures. Power from the country's much celebrated Renewable Energy Independent Power Producers Programme (REIPPP), initiated in 2011, starting generating power in 2014 but the quantities are as yet still insufficient to cover the shortfall. The country's Demand Side Management (DSM) Programme, operated by Eskom, had delivered verified savings of 3,500 MW **[1]** since its inception in 2007 but was suspended in October due to budget constraints. Eskom generates more than 95% of the country's electricity. In December, 2014 the Minister of Public Enterprises, Eskom's sole shareholder, warned that it is '*going to be very tough for about two years longer and patience will be needed on the part of all citizens'.* Since that declaration the country has been experiencing rolling electricity blackouts on a daily basis.

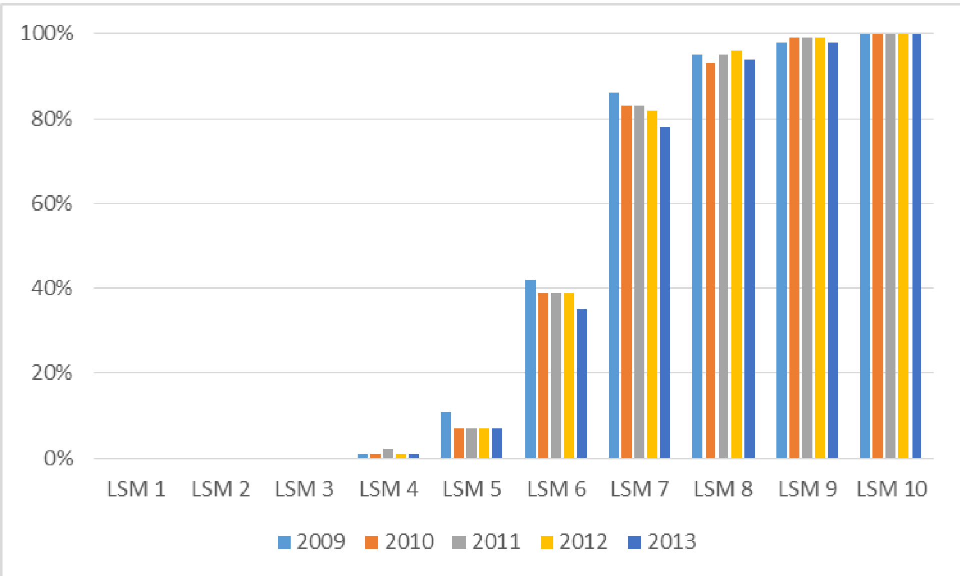
Under these circumstances all efforts to reduce consumption become significant. South Africa's residential sector can play a meaningful role not only because it is the second largest consumer of electricity but because of how it influences demand. The residential sector accounts for approximately 17% of electricity use in South Africa, but as much as 35% during peak periods **[1]** (Figure 1).



Source: Eskom (2012)

Figure 1: Sectoral electricity consumption and peak period demand

As recently as the late 1980's the country's electrification rate for residential households was low (35%), whereby almost all white households had electricity and the electrification rate of non-white households was extremely low. An electrification programme was implemented in the early 1990's and by 2001 the electrification rate had increased to 61% **[2]**, by 2011 it was 83% **[3]**. By the late 1990's the country's electrification programme expanded the market for electrical appliances by an estimated 50% **[4]**. But the country's high income inequality segregates the population **[5]** and means that different residential segments have very different consumption profiles. The Living Standards Measure (LSM) is the most widely used marketing research tool in South Africa and measures affluence by dividing the population into 10 groups, 10 (highest) to 1 (lowest). Groups 1-4 are low income or indigent (3.8 million households in 2013), 5-8 middle class (8.9 million households in 2013) and 9-10 represents upper income (2.3 million households in 2013). One of the questions asked in the annual survey is: '*Do you have hot water from a geyser? (electric water heater)*' The responses for the period 2009-2013 are shown in Figure 2.



Source: All Media and Product Survey (AMPS)

Figure 2: Penetration of WH by LSM group 2009 - 2013

As can be seen in Figure 2 only middle and high income households use electric water heaters. The lower middle and indigent households source their hot water from electric kettles or by boiling large pots of water. This may be done on an electric stove or from a coal or wood fire. A study conducted by Eskom (2013) **[6]** found that the average middle income household uses between 750kWh and

1,100kWh per month, of which the WH is the biggest consumer accounting for 39%. The second biggest consumer of electricity is space heating (16%). WHs have thus been correctly targeted for electricity savings for many years by: 1) Consumers looking to reduce their electricity bill; 2) Government to achieve its energy savings targets under the National Energy Efficiency Strategy and its international commitments to reduce greenhouse gas emissions; and 3) Eskom under its DSM programme and to manage peak demand, by offering a rebate on Solar Water Heaters (SWH) and Heat Pumps (HP) and a free WH blanket to improve the insulation and thus reduce standing losses.

Two opportunities exist for energy savings from WHs. The first is to improve the existing technology used to heat the water, which is electric resistance elements, by migrating to gas fired boilers, SWH or HP. The second is to minimise heat losses. This country's S&L programme targets the second opportunity and limits itself to improving insulation efficiency at the manufacturing stage.

Evolution of the Water Heater Market in South Africa

The manufacture of WHs, has evolved slightly differently as compared to the other large residential appliances. This is in line with the way the electric WH market has developed internationally where there is a large variation in the product class and use of hot water. Climate and culture play important roles in the need for hot water and dictate the practices of its use. This wide variation in climate and culture is correlated to the variation in type and size WHs used in households and available locally. Colder and wealthier countries tend to use large storage tank WHs. In warm-climate countries, if households have a dedicated WH at all, these units tend to be smaller and are not turned on continuously. Electric resistance storage tank water heaters are most common in South African households **[7]**. Gravity fed WHs dominated the market up until the 1950's. In the 1960s 100 kPa copper WHs entered the market followed by 400 kPa steel WHs in the 1980s. Steel WHs were transformed to 600 kPa in the 1990s, which became and remain the market standard. Fibreglass and plastic WHs were also introduced in the 1990s but these make up a very small percentage of the market. Copper WHs are now virtually redundant **[8]**. The use of gravity fed WH required that they be placed at the highest point in a house. This meant that all residential WH were installed in the space between the ceiling of the top floor and the roof, or attic. With the introduction of pressurised WHs it was no longer necessary to install the WH in the attic, but the practice was entrenched and architects continued to design and specify that WHs be installed in the attic. In addition WHs are installed directly above the bathroom which they service. It is not uncommon for large houses to have as many as three WHs. All bathrooms must have access to an exterior wall for effluent plumbing requirements and with minimum dimensions of 1.1m X 0.6m are not able to fit vertically in this limited space due to the pitch of the roof. To overcome this WHs were installed in a horizontal rather than a vertical position. These unique practices as well as other factors such as the quality of the water in different geographical areas with some regions having particularly hard water (high content of calcium and magnesium), the relatively straightforward technology needed to manufacture WH and the high costs to import them due to their physical size and low value and national standards which have evolved to serve the local market means it is not economically viable or practical to import units and almost all WHs in South Africa are locally manufactured. Kwikot, the country's oldest and dominant manufacturer with a market share in excess of 65% was established in 1903. The rest of the market is made up of smaller companies, two of which control a further 25% and the balance is made up of small privately (family) owned business which serve regional or local markets. A few high end products are imported such as gas fired water storage heaters but these are niche serving the top end of the market and have a negligible market share.

WHs enter the market in one of two ways. It is a contractual requirement for all houses that are financed (bonded) to take out building insurance. This insurance covers all fixtures and WHs installed on the property are insured. Should a WH fail households contact their insurance company and not a plumbing service. The insurers outsource this function to plumbing companies who install a new unit within 24 hours. Other than reporting the incident, the household has little involvement in the process. This practice accounts for over 60% of annual sales. The other 40% of the market is made up of sales to newly built houses or renovations, and once again the owner is generally not involved as the WH is sourced and installed by the contractor responsible. In both instances the decision makers have no incentive to install a more efficient model, which in all likelihood is probably more expensive. Their only obligation is that the WH installed is certified and meets the mandatory health and safety requirements as set out by the South African Bureau of Standards **[9].**

South Africa's Standards and Labelling (S&L) Programme and National Standards

The Energy White Paper (1998) was lauded as a progressive policy document that aimed to liberalise the market by introducing independent power producers (IPP) and supporting the introduction of renewable energy and energy efficiency. The Paper specifically addressed residential appliances under the section of Energy efficiency in par. 3.5.3: 'A domestic appliance-labelling programme may also be introduced' **0**.

The National Energy Efficiency Strategy (NEES) issued by the South African Department of Minerals and Energy (now Department of Energy - DoE) in 2005 set a national voluntary target for EE improvement of 12% by 2015 (using a 2000 baseline). Under the residential sector the NEES states '*Appliance Labelling with Minimum Performance Standards*' as one of the four interventions **[11]**. In the same year the DOE introduced a voluntary labelling scheme, which was a precursor to a mandatory Standards and Labelling (S&L) Programme. The voluntary scheme targeted refrigerators but encouraged manufacturers to extend it to all their appliances. The voluntary programme had limited impact. With no support or signals from Government on the implementation of a mandatory programme it was soon forgotten and abandoned by manufacturers and retailers. In 2007 the South African DoE and the United Nations Development Programme (UNDP) country office agreed to submit a joint application to the Global Environment Facility (GEF) for financial support to implement a mandatory S&L programme Error! Reference source not found..

An imperative for the South African Government was that the introduction of a mandatory S&L programme does not exert any excessive pressure on local manufacturers and consumers. To properly assess the situation and provide local manufacturing an opportunity to provide input, an impact analysis study was commissioned by the Department of Trade and Industry and sponsored through the Fund for Research into Industrial Development, Growth and Equity, FRIDGE (2011) Error! Reference source not found.. The objective was to determine the baseline performance (base case) of residential appliances in the market, how these compared to locally manufactured models, and identify a MEPS level that would maximise energy savings with an acceptable impact to manufacturers and consumers. The findings of the study would be used as a benchmark for the MEPS to be adopted. The large energy savings potential from WHs made them a natural inclusion in the country's S&L programme. Standing losses from WHs in South Africa are high and exceed 2 kWh per day or 730 kWh per annum **[7,13]**. An improvement of 15% or more amounts to over 100 kWh in yearly savings per unit for the household. With a minimum of 450,000 WH being sold annually savings of this order are significant in terms of avoided generation and reduced GHG emissions **[13].**

WHs, unlike the other appliances selected for the country's S&L programme, were already subject to energy performance requirements. All WHs must attain SANS 151 **[14]** certification before they can enter the market. This national standard includes a maximum allowable standing loss per 24 hours. For the two most popular models in the market, the 150 L and 200 L it is 2.59 kWh and 3.02 kWh respectively. These levels were set when high pressure steel WHs were first introduced and have not been revised since. The development of standards consider health, safety and environment. Where personal injury may result the South African Bureau of Standards will set the minimum requirements. The remaining requirements are developed by technical committees (TC) made up of industry, Government and any other interested parties. Requirements are agreed by the TC based on mutual consensus and reaching agreement can be contentious due to the vested interests of the numerous participants. Under this arrangement it is often the case that the lowest common denominator is adopted.

An outcome of the latest review of the SANS 151 in 2011 was the introduction of an energy performance label that would be affixed to all WH. No improvements would be made to the existing standing loss requirements. The WH industry was approached to participate in the FRIDGE study but only two manufacturers, who jointly controlled < 5% of the market, agreed to participate. The rest of the industry argued that they fell under the SANS 151 process. As a result the FRIDGE study was not able to complete a detailed analysis **[13]**. A public meeting hosted by the National Regulator for Compulsory Specifications (NRCS) in 2012 to discuss the adoption of improved MEPS was met with fierce opposition from the industry. The reasons cited where as follows:

- WHs fall under SANS 151 and not the S&L National Standard (941).

- An international survey undertaken by the industry found that the existing standing loss requirements in South Africa are amongst the highest in the world.
- There is growing international consensus that the standing loss approach is an outdated and ineffective measure to improve energy performance. A more appropriate test is the simulation test which the EU was developing. It would be more prudent to wait for the outcome of EU regulations and then customise these for the South African market.
- Due to the structure of the market the purchaser of the WH is not the end user making, S&L a consumer oriented programme, ineffective.
- WH sizes in South Africa are not random but based on standard cut steel sizes and access points into the attic.

The industry concluded that the proposed requirement to improve the energy performance via increased insulation would mean a disproportionate increase in costs due to retooling requirements, customised steel sheets and additional effort to access the attic. These costs would be substantial would result in a net cost to the consumer. After considering all representations a communication was put out in 2013 by the NRCS **[15]**:

In light of these comments, lack of agreement in the EU and elsewhere, and available evidence, the Government authorities have concluded that there is insufficient reliable information regarding SA needs for more efficient water heating systems to take a decision on MEPs for water heaters. The FRIDGE study is useful but the conclusions are open to question due to the small number of local manufacturers that participated.

It was decided that further research into the efficiency of water heaters is necessary before taking any decisions on MEPs and a timetable for implementation. At least a year is required to complete such a study, and terms of reference will be drafted and tenders called for. SANEDI is investigating sources of funding.'

The NRCS statement did not address the question of costs and it is questionable as to whether NRCS had any real intent in sourcing the required funding, or whether it was even likely that SANEDI would be able to source the funding, without which the study could not be undertaken. The NRCS position implied that it was unlikely that the MEPS for WH would be improved in the short to medium term. As GEF funding is based on GHG reductions the entire S&L programme was at risk as the removal of WHs meant that the forecast energy and resultant GHG savings of 3.8 TWh by 2030 would be halved **[13].** The need for a technical study was therefore crucial but a year had passed and still no funds had been allocated. International funding for the study was secured from SEAD as a consequence of the ongoing relationship between LBNL, who collaborated in the FRIDGE study and identified the relevance of such a study, and their decision to appoint a local consultant to provide input and advice to the local S&L project team and feedback to SEAD itself who are not based in the country.

International Cooperation and Technical Studies

As a signatory to the Clean Energy Ministerial (CEM), South Africa's S&L programme has received technical support since 2011 from the Lawrence Berkeley National Laboratory (LBNL) through the Super-Efficient Appliance Deployment (SEAD) Initiative. It was resolved to try and overcome the technical and information barriers which were delaying decision making by undertaking a series of studies to address the concerns raised by industry, many of which were anecdotal but difficult to dispute due to the lack of available and credible research.

International Survey of Electric Tank WH Efficiency and Standards

A paper was presented by LBNL and Unlimited Energy at the South Africa Energy Efficiency Conference (November, 2013), which surveyed international WH efficiency and standards **[7]**. The paper compared the various test parameters used around the world and assessed if in fact it was true that the existing MEPS for WH in South Africa are among the best in the world. The study found that the approach used in South Africa is not dissimilar to the ones employed in other major economies (Table 1) and therefore comparable. In stark contradiction to the claims made the WH industry that South Africa has among the highest MEPS, the country was found to have weak MEPS (Figure 3), and as a result large savings for standing loss improvements exist.

Table 1: Test Parameters for Electric Storage Tank Water Heaters

Economy	Test Parameters
South Africa	48 hour standing loss test, Δt 45°C
India	Standing loss test, Δt 45°C
European Union	Proposed, simulated use test. Eight draw patterns. Separate standing loss test for hot water storage tanks
United States	Simulated use test, six draws at one hour intervals, Δt 37,5°C

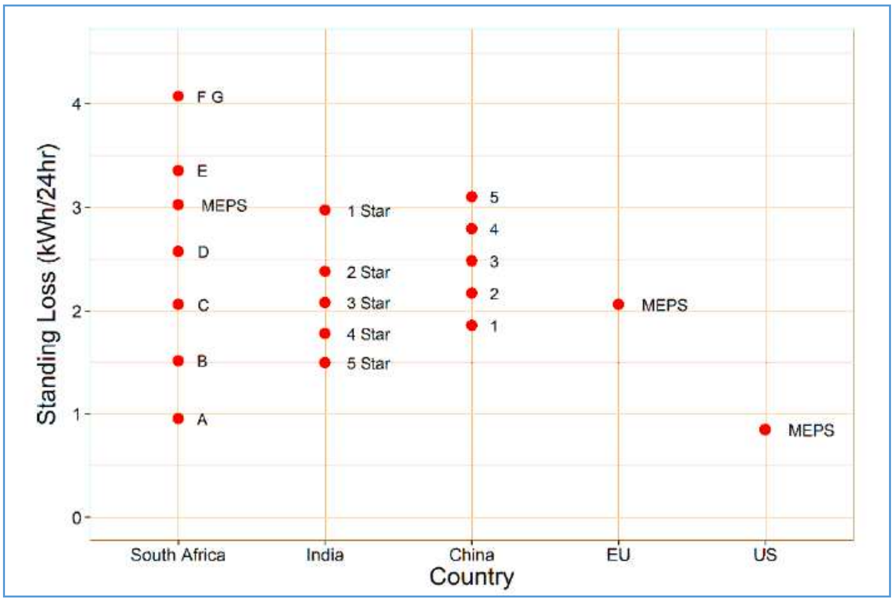


Figure 3: Comparison of standby loss requirements for MEPS and labelling categories for 200L WH

Water Heater Insulation Cost-Effectiveness Study

The findings of the international survey provided sufficient evidence for a detailed techno-economic analysis, which was broken into two separate studies, namely a technical study funded by SEAD and an economic study funded by S&L programme. The objective was to determine the projected cost to manufacturers and consumers to reduce WH standing losses to varying degrees in order to formulate MEPS supported by analysis of net financial impacts to consumers.

To gauge the distribution of performance of the WH market, 5 models were selected, purchased and subjected to testing. Due to a high degree of consolidation in the market, the sample was estimated to represent close to 90% of the market in the most common capacity category of 150 L. Each WH was then subjected to the following four sub-tasks **[16]**:

- *Product testing:* The WH was tested according to the national standing loss test procedure. These test measurements formed the technical baseline of the study.
- *Product tear-down measurements:* The WH was disassembled to determine the corresponding engineering configuration of the baseline.
- *Component cost determination:* Market information on material and labour costs was gathered.
- *Standing loss and cost determination:* The impact of additional insulation was modelled and the final costs to manufacturers and consumers was calculated.

The findings of the study are summarised in the Table 2 below.

Table 2: WH Insulation Cost-Effectiveness Study

Activity	Finding

<table>
<tr><td>Standing Loss Test</td><td>All units were found to be in compliance of the current MEPS;
Adjusted standing loss measurements ranged from 1.87 kWh/24hr to 2.54 kWh/24h in the horizontal position, placing one model in the ‘C’ category, 4 in the ‘D’ range and one in the ‘E’ range;
Significant differences were found in test results between the horizontal and vertical configurations; and
Ambiguities in the test procedure configuration specifications were found to produce significant variation in results.</td></tr>
<tr><td>Tear Down Analysis</td><td>The thickness of insulation averaged over different parts of the tank ranged from 20-26mm, but was highly non-uniform for some models</td></tr>
<tr><td>Cost Effectiveness of Increased Insulation</td><td>Cost-effectiveness indicators were calculated for various levels of insulation. The indicators used were: 1) Incremental Life Cycle Cost (ΔLCC); 2) Payback Period (years) and; 3) Cost of Conserved Energy (CCE)
<table>
<tr><th>t
mm</th><th>ΔLCC
R (EUR)</th><th>Payback Period
year</th><th>CCE
R (EUR)</th></tr>
<tr><td>20 (baseline)</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>25</td><td>-1,486 (110)</td><td>0.15</td><td>0.05 (0.005)</td></tr>
<tr><td>50</td><td>-4,596 (350)</td><td>0.30</td><td>0.10 (0.01)</td></tr>
<tr><td>75</td><td>-5,595 (430)</td><td>0.47</td><td>0.16 (0.01)</td></tr>
<tr><td>100</td><td>-6,010 (460)</td><td>0.66</td><td>0.23 (0.02)</td></tr>
<tr><td>125</td><td>-6,173 (475)</td><td>0.87</td><td>0.30 (0.025)</td></tr>
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The overall findings of the study were as follows:

- WH are compliant with current regulations, but show significant opportunities for further reduction of standing losses.
- Increasing insulation thickness is demonstrably cost-effective from the consumer standpoint in terms of increased material costs well beyond the 50mm level considered to be feasible by manufacturers.
- As a result of this, and in light of other heat losses, a ‘B’ level is likely achievable by WH manufacturers and cost-effective to consumers.
- Ambiguities in the current test procedure language and methodology may result in large variation in results and should be reviewed to increase precision. These include aspects such as the nature of external pipe fittings present during the test, positioning of the internal temperature sensor relative to the heating element, exact temperature control range boundaries during test, orientation specifics, etc.

The WH industry was consulted extensively during the study to address the issues identified by the industry. Table 3 lists the issues and how each of these were addressed.

Table 3: WH Industry MEPS Improvement Concerns and Steps taken to address them

Industry Concern	**Actions Taken to Overcome Barriers**
WHs fall under SANS 151	Largely a ruse used by the industry to delay proceedings. This was overcome through cooperation between the DOE and SABS who confirmed that an industry can be compelled to comply to multiple standards and regulations as long as they are not contradictory
SA WH MEPS are already amongst the highest in the world	The international survey on WH efficiency and standards **[7]** dispelled these claims. The findings of the paper were not questioned by the industry
Standing loss test is outdated. Wait for EU to develop simulation test	Although the EU is developing a simulation test, a standing loss test is still required. It was incorrect of the industry to imply that a standing loss test would become redundant

Purchaser of WH is not the end user	For the economic analysis, the insurance industry was approached and found to be supportive of more stringent MEPS. The additional increase to monthly premiums was very low. For the building trade, contractors must buy SABS approved WHs and any additional costs will be passed on to the consumer, which are cost effective and thus beneficial
Costs associated with retooling make increased insulation prohibitively expensive	The technical study found that increased insulation was cost effective as shown in Table 2

The final results were presented to all stakeholders at a meeting hosted by the DOE in November, 2015 where all manufacturers, except one[1], confirmed that: 1) a 'B' energy class is possible; 2) energy class 'B' can be achieved within one year of the industry being notified of the requirement to do so; and 3) the retail price of WH would not increase by more than R300 (EUR23). In return, the WH industry required a clear timetable and a commitment that all manufacturers would be required to comply with the MEPS when it came into effect. The use of incentives was raised and is to be considered in 2015 by the DoE and National Treasury. In January, 2105, the DoE is initiating the process to revise the MEPS for WHs from energy class E to B.

Conclusion

The WH industry opposed all efforts to improve the existing MEPS. A study undertaken by the Government to assess the impacts of moving from energy class E to D or C failed as it met with resistance from the majority of the industry who provided seemingly compelling, but unsubstantiated, evidence as to why an improvement was not feasible. Access to international technical experts to conduct empirical research to ascertain the validity of the industry's concerns, supported by the South Africa Government, found the contrary and that a move to an even higher energy class (B) is cost-effective. The energy savings are significant as the maximum allowable standing losses for a 150 L will decrease from 2.59 kWh to 1.38 kWh per 24 hours, i.e an improvement of 46%. It is unlikely that this result would have transpired without the close cooperation of the international and local entities supporting the S&L programme and the funding made available by the international agencies.

At a more general level although the South African Government committed itself to a residential S&L programme as far back as 1998 almost no implementation took place. It is also unlikely that the programme would have: 1) Commenced without GEF funding ($4.3 million); and 2) Whether barriers would have been addressed to the extent that they have without the international technical assistance received from organizations such as SEAD. There are several reasons for this but key amongst these is that such projects are considered low priority, especially in a context of low electricity tariffs and an over-supply of electricity which was the position South African was in until mid-2000; there is generally a shortage of skills and priority within Government institutions to conduct such technical studies and / or a shortage of funds to contract private skills to undertake the work; and finally, such initiatives require the co-ordination of multiple Government institutions.

In the South African experience, it is thus fair to conclude that the implementation of a residential S&L programme is a direct result of international funding and the progress made to date has been supported and advanced through international technical cooperation.

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Recommendations for an adequate policy package to support highly efficient and ultralow emission small-scale residential biomass combustion technologies in Europe

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Abstract

Small-scale residential biomass combustion for space heating and warm water production already holds a considerable share on overall energy production from biomass in Europe [1]. In the existing regulative framework of EU air quality and climate protection targets, an extended usage of renewable biomass heating without an increase of harmful emissions is urgently needed [2]. In this context, the FP7 project 'EU-UltraLowDust' (ULD) aimed at the demonstration of highly efficient and ultra-low emission small-scale biomass combustion technologies and the development of supporting policy recommendations [3].

New combustion technology operating at almost zero particulate matter (PM) emissions has been demonstrated, rivalling even the performance of state-of-the-art natural gas fuelled systems. In this context, the authors analysed EU policy options for a faster diffusion of these new innovative technologies. The analysis presented in this paper is based on results from an original impact assessment with special focus on energy efficiency and emission scenarios, including the potential effects of a broad deployment of the new ULD technologies as well as the early replacement of poor performing existing installations.

As the derived results show that major shares of energy consumption and emissions from residential biomass combustion in the EU are caused by old heating systems, specific policy measures for new and existing installations have been analysed. Following this, a recommended and harmonized policy package for new Small Combustion Installations (SCI) to be put on the market as well as for existing SCI in the stock has been developed, which will be presented in this paper. The basic policy package addresses new installations and consists of a two-step approach, aiming at enhancing the current and forthcoming policies addressing the SCI market in Europe. A complementary second policy package for existing installations aims specifically at the early replacement of SCI already installed in the stock, which are characterized by low efficiency and high emissions.

Introduction

Small-scale residential biomass combustion for space heating and warm water production already holds a considerable share on overall energy production from biomass in Europe [1]. With the "202020" goal of providing 20 % primary energy from renewable sources by 2020, the EU Directive "on the promotion of the use of energy from renewable sources" (2009/28/EC) expects also to increase sustainable solid biomass combustion significantly [4], which however requires additional efforts and incentives by the EU and the member states (MS).

Considering the existing regulative framework for achieving EU climate protection and air quality targets, an extended usage of efficient renewable biomass heating and a significant reduction of harmful emissions are needed at the same time. Especially particulate matter (PM) emissions have been identified as hazardous to health [2] and therefore, in the EU Directive "on ambient air quality and cleaner air for Europe" (2008/50/EC), a daily mean limit value of 50 µg/m^3 PM_{10} is defined for the protection of human health, which shall not be exceeded more than 35 times per calendar year [5]. However, even the most recent measurements show that this defined limit is still exceeded regularly in many areas all over Europe. Next to the transport sector, solid fuel combustion has been identified as one of the main sources for this ambient air pollution regarding PM, especially originating from poor performing out-dated residential stoves (direct heaters) and boilers (indirect heaters).

In this context, the FP7 project ‘EU-UltraLowDust’ (ULD) [3] aimed at the demonstration of highly efficient and ultra-low emission small-scale biomass combustion technologies for direct and indirect heaters as well as the development of supporting policy recommendations.

To reach these aims, a consortium had been formed, consisting of the manufacturers of the analysed key technologies as well as research institutions, which supported the industrial partners with their expertise. For wood pellet and wood chip combustion in indirect heaters a new highly efficient boiler technology (“UleWIN technology”, whereby Ule is the abbreviation for ‘Ultra low emission’ and WIN is the abbreviation for the company name) operating at almost zero detectable PM (in terms of Total Suspended Particles, ‘TSP’), OGC (Organic Gaseous Compounds) and CO (Carbon monoxide) emissions has been demonstrated, rivalling even the performance of state-of-the-art natural gas fuelled systems. Moreover, a new energy efficient wood log stove technology (APS technology, standing for “Active Power System”) with optimized air staging and automated control system has been developed for direct heaters.

As the project also aimed to develop policy recommendations considering the results achieved by the new technologies, EU policy options for a faster diffusion of the most innovative technologies and their possible impacts have been assessed. Since major shares of the energy consumption and emissions from residential biomass combustion technologies in the EU are caused by out-dated old heating systems, specific measures for new products to be put on the market as well as for existing installations in the stock have been analysed and discussed with several relevant stakeholders in this area:

- Stringent Emission Limit Values (ELVs) for new installations, going beyond the level of current Best Available Technology (BAT), which could be e.g. part of a possible future revision of the EU Ecodesign regulations for Lot15 (solid fuel boilers) and Lot20 (local room heaters).
- Product labels, which allow a better visibility and promotion of the most innovative next generation technologies on the market.
- Ambitious new regulations with ELVs also for existing installations, as the emission reduction potential through replacement programs is very high.
- Incentive programs to foster a voluntary early replacement of inefficient existing installations with the most innovative new technology.
- Supplementary actions to further decrease the environmental impact of biomass small combustion installations in general (e.g. addressing user behaviour and fuel quality).

Based on this a recommended and harmonized policy package for new Small Combustion Installations (SCI) to be placed on the market as well as for existing SCI in the stock has been developed, which will be presented in this paper. The basic policy package addresses new installations and consists of a two-step approach, aiming at enhancing the current and forthcoming policies addressing the SCI market in Europe. A complementary second policy package part for existing installations aims at the early replacement of SCI already installed in the stock, which are characterized by low efficiency and high emissions.

As outlined above, there are strong arguments to increase small-scale renewable biomass solid fuel usage in the European heating market for greenhouse gas (GHG) emission reduction purposes and to reduce also health-relevant emissions at the same time through the market diffusion of significantly improved combustion systems such as the new technologies demonstrated in the ULD project. In order to show the urgency of an accelerated market and stock transformation by means of SCI specific policy instruments, this paper presents in its first part a technical efficiency and emission reduction potential analysis for Europe. For this purpose different scenarios have been assessed by means of a stock modelling approach. In the second part of the paper, the synergetic policy options and recommendations are comprehensively presented and discussed.

Analysis of the efficiency and emission reduction potential in Europe

During the ULD project an impact assessment was performed to assess different scenarios for solid fuel Small Combustion Installations in the EU market, paying detailed attention to energy consumption and emissions for following product categories: logwood boilers, logwood stoves, wood pellet boilers and wood chip boilers. Together, these product categories cover the most significant part of the solid fuel SCI market in Europe in terms of energy consumption. According to the Ecodesign preparatory study for Lot15 and 20 these categories combined account for 63 % of the overall solid fuel consumption in the EU27 (logwood boilers: 45 %, logwood stoves: 8 %, wood pellet boilers: 8 % and wood chip boilers: 2 %). Furthermore these product groups are also characterized by significant additional technical efficiency and emission reduction potentials (e.g. in contrast to already better performing pellet stoves, which are a relatively new and advanced technology using also high-quality standardized fuels).

The performed impact assessment considered the final performance parameters achieved by the demonstrated new ULD technologies as well as scenarios to show the improvement potentials, which should be addressed by adequate policies and measures:

- In the "Business as Usual Scenario" (BAU) only Base Case products (typical products on the market) will be purchased in the future. This is the baseline reference scenario.
- In the "Ecodesign" scenario, as of 2022, every new SCI purchased on the EU market fulfils the requirements of the Lot15/20 Ecodesign implementing measures as adopted by the Ecodesign Regulatory Committee in October 2014 [6][7]. Therefore, beginning in 2022, 100 % market share for products complying Ecodesign is assumed.
- In the ULD scenario, as of 2022, every new product will be an ULD product. Assumption: ULD technology has 100 % market share as of 2022, in order to show the additional technical improvement potential of the new technologies.

For the purposes of this paper the focus is lead on energy efficiency and PM (in terms of Total Suspended Particles, 'TSP') as the most health relevant category of emissions from solid fuel SCI.

The following Figure 1 shows the development of the annual solid fuel consumption for all ULD product groups (direct and indirect heaters) combined. Due to the assumed general reduction effect of the EPBD (Energy Performance of Buildings Directive, 2010/31/EU) [8] on the heat demand of the building stock in Europe and the autonomous replacement of old (and typically inefficient) end-of-life products, the overall energy consumption of SCI can be reduced after reaching a peak of 1,927 PJ/year in 2024, although the stock of installed SCI is expected to double until 2050 (absolute decoupling). While a general decoupling can already be reached in the Business As Usual (BAU) scenario, Ecodesign with Minimum Energy Performance Standards (MEPS) and especially the innovative ULD technology would allow to achieve even larger savings.

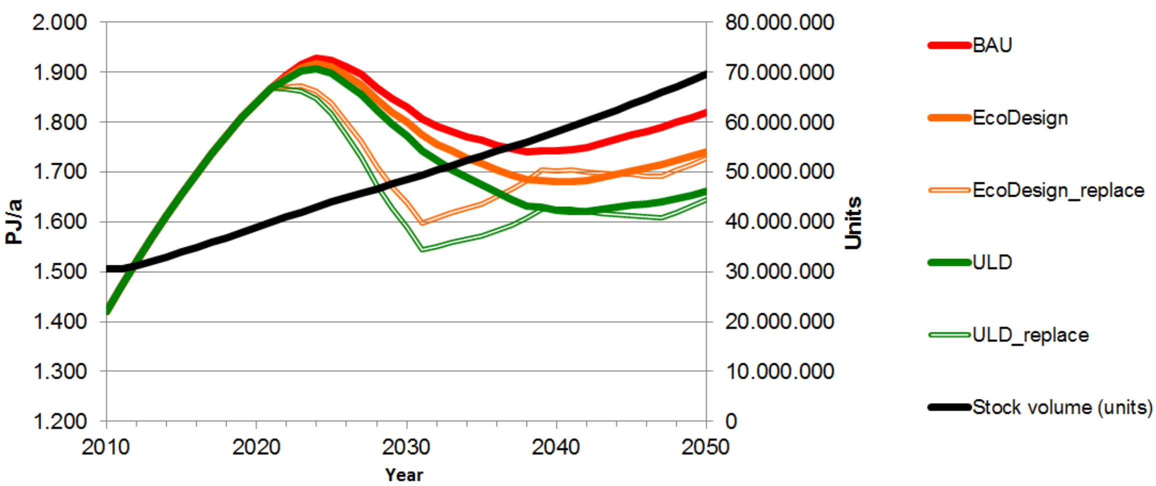

Figure 1: Development of solid fuel consumption in the different scenarios (EU27)

Source: Own calculations by the authors based on Ecodesign preparatory study and ULD project

However, in all scenarios addressing the market (and therefore solely new products) the full efficiency improvements will be reached only after several years, since solid fuel combustion installations are characterized by a long technical lifetime (typically about 20 years for boilers and more than 25 years for stoves). Thus, for the ULD and Ecodesign scenarios, an additional early replacement option has been considered respectively (see *_replace* scenarios): As of 2022, any existing "old" SCI in the stock with 10 years remaining lifetime will be replaced by a new one, which complies with the regulatory performance requirements for new products of the respective scenario in the year of purchase. Thereby, the *_replace* sub-scenarios show that addressing existing SCIs in the stock would especially allow harnessing the significant efficiency and emission reduction potentials much earlier. Based on the same general assumptions, the following Figure 2 shows also the TSP emission reduction potentials for all ULD relevant SCI product groups combined. Due to the general reduction effect of the EPBD and the autonomous replacement of old end-of-life products with typically high emissions, the TSP emissions in the BAU scenario can be hold steady close to 110,000 t/year in the next decades, although the stock of installed SCI is expected to double in the same period (relative decoupling).

The implementation of Ecodesign regulation for Lot15 and 20 with specific emission limit values (ELVs) has the potential to reduce also other environmental impacts than energy consumption of solid fuel SCI. Accordingly, in the Ecodesign scenarios an absolute decoupling of the total TSP emissions and the number of installed heating systems is possible. This underlines that the possibility to include relevant non-energy aspects in Ecodesign implementation measures is highly beneficial to enable major co-benefits of energy efficiency. Additionally, the calculations also show that Ecodesign measures with ELVs should be implemented as soon as possible, as any delay would mean the loss of several thousand tons of possible PM (TSP) emission savings per year.

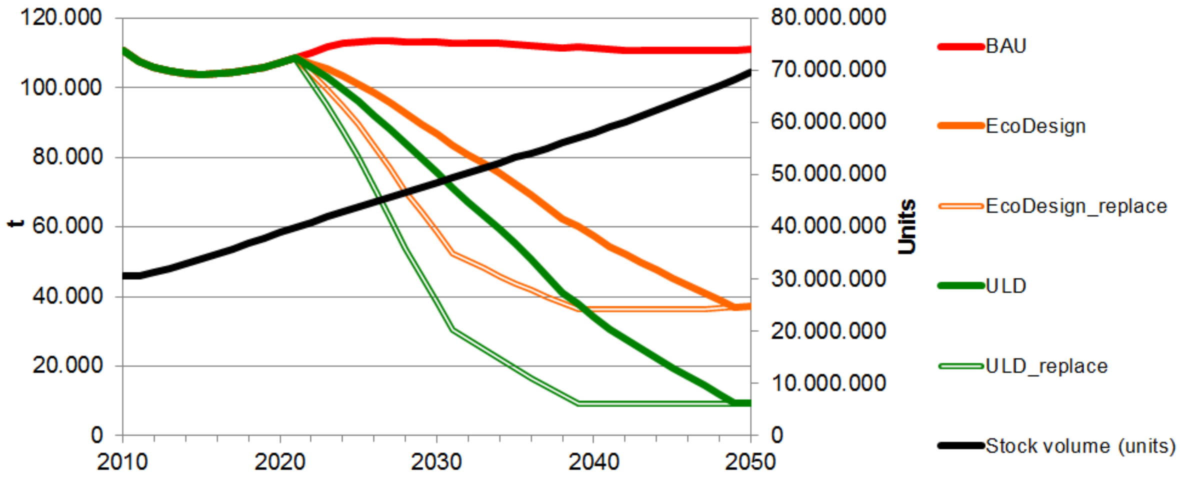

Figure 2: Development of PM (TSP) emissions in the different scenarios (EU27)

Source: Own calculations by the authors based on Ecodesign preparatory study and ULD project

The demonstrated new ULD technologies would even have the technical potential to reduce the overall PM (TSP) emissions to a much greater extent down to 9,469 t/year by 2050 (-91 % compared to BAU and -74 % compared to Ecodesign in the same year). Thereby, the *_replace* sub-scenarios show strong evidences that especially the early replacement of inefficient existing SCI in the stock with high emissions is playing a key role for a significantly accelerated reduction of overall emissions and related negative health effects. Based on results of the performed quantitative analysis, it can be clearly stated that without further and significantly accelerated technical improvements as well as adequate new policy measures for logwood stoves, wood log-, wood pellet- and wood chip boilers the full efficiency and emission reduction potential in the EU cannot be achieved. Without encouraged policy intervention, long-term negative lock-in effects as consequence of prolonged sale and usage of inefficient SCI with elevated emission levels would delay for decades the achievable economic, ecologic and social (health) benefits of innovative new technologies and therefore also the full realisation of the important GHG emission reduction potential of renewable biomass usage.

Discussion: Policy options and recommendations

Why further policies are required

Currently, there are already efforts by the EU and Member States to implement policies and measures for SCI with the intention to increase energy efficiency and to address air quality (see Figure 3). As shown by the scenario calculations, the implementation of Lot15/Lot20 Ecodesign measures with requirements for higher energy efficiency and much lower specific emissions for SCI [6][7] has the capability to improve the situation already to a relevant extent. Thereby, the performed calculations confirmed in particular the importance and effectiveness of EU Ecodesign as instrument to increase energy efficiency with the ability to trigger highly relevant co-benefits at the same time. From an economical perspective, the investment costs for products fulfilling Ecodesign requirements are often also comparable to Base Case products, so that end-users could even realise a cost advantage by energy cost savings at the same time as a result of more fuel-efficient products complying with Ecodesign requirements.

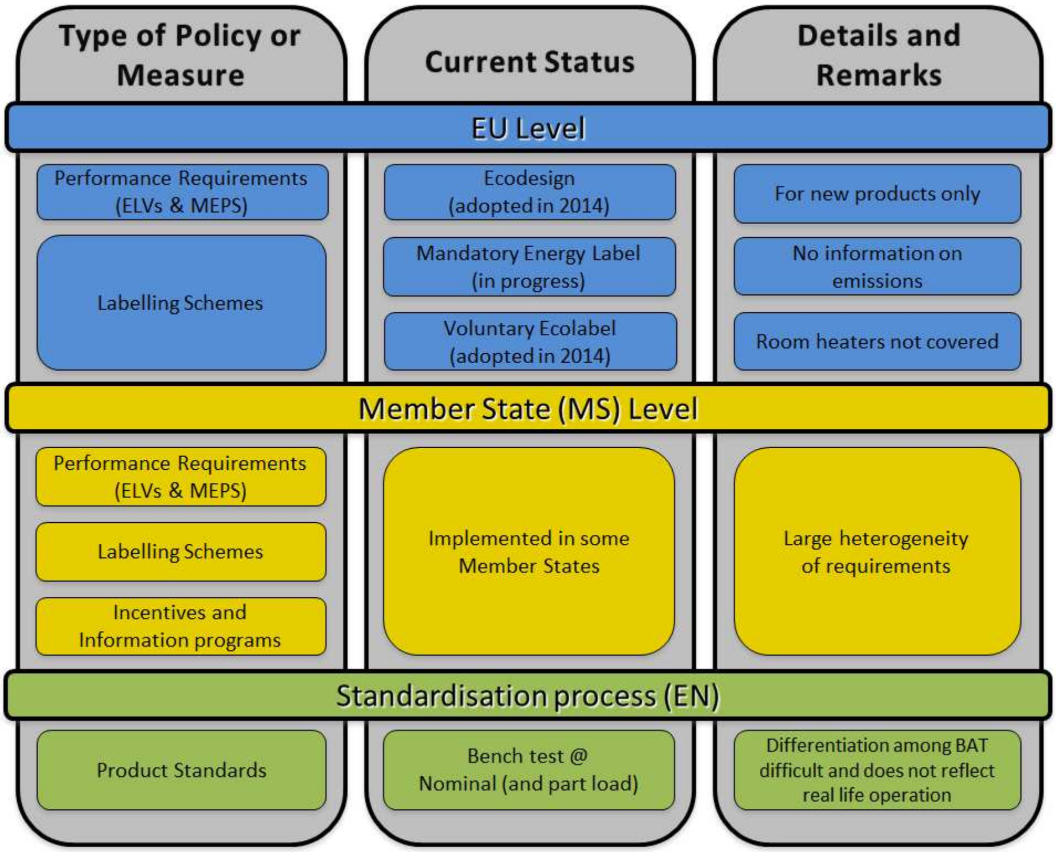

Figure 3: Current status of the policy package for new biomass solid fuel SCI (EU28)

Source: Own illustration by the authors based on ULD project

Beyond Ecodesign, the technologies demonstrated in the ULD project would have the potential to reach even larger energy and emission savings in a much shorter time period. However, all new systems developed in the ULD project are still more expensive than comparable Ecodesign or Base Case products. This is related to the typical higher initial investment costs of new technologies, which are not fully compensated by lower operation costs, as the fuel efficiency aspect alone can already be pushed near to the upper technical limit by Ecodesign or BAT products. In addition, there are currently no adequate financial rewarding schemes for the achievable emission reductions by the ULD technologies. Although the problem of higher initial investment costs could be overcome gradually by economies of scale, this is another reason, why specific policies and measures will be necessary to support a much faster and deeper market diffusion of the most advanced technologies in order realise the full technical energy efficiency and emission reduction potential.

For this purpose and in the light of the results achieved within the ULD project, the developed complementary policy packages for new SCI to be placed on the market as well as for existing SCI in the stock are subsequently described and discussed in detail.

Recommended basic policy package for new SCI

General policy package approach

In order to overcome effectively the existing major market barriers and obstacles, transformation towards better performing technologies has to be initiated by “push” measures with binding minimum performance standards like EU Ecodesign with mandatory requirements for efficiency (Minimum Energy Performance Standards) and for emissions (Emission Limit Values). In accordance with EU Directive 2009/28/EC, additional “pull” measures like labelling schemes (e.g. EU Energy- and Ecolabel), financial incentives or Green Public Procurement as well as information and training programs for users and installers (including certification) are also crucial to support a much faster and deeper market transformation. As experiences show, well-coordinated bundles of such policy instruments can form a synergetic and much more effective “policy package” [9].

Two steps of improvement

Although some EU policy instruments have been implemented or are prepared for final implementation (Figure 3), there is still no holistic policy package approach for SCI on EU-level yet. Additionally, some of the instruments, like the forthcoming EU Energy Labelling, cover only energy efficiency and will therefore not be sufficient to harness also important co-benefits (e.g. reduction of SCI related emissions) at the same time. In this context a two-step policy evolution approach for new SCI is recommended in order to create a comprehensive policy package addressing the market of SCI on EU-level more effectively (see Figure 4 below):

- **Step 1:** Implementation of further developed “pull measures”, which are based on existing bench type testing methods for SCI products. This may in particular include the EU Ecolabel, a revised EU Energy Label with emission information directly on the label as well as EN product standards including new product performance classes.

- **Step 2:** Major revision or development of new EN standards, considering the latest technological progress and more realistic operation testing conditions for efficiency and emissions. At the end of Step 2, the entire SCI policy package will have to be updated according to the new EN standards.

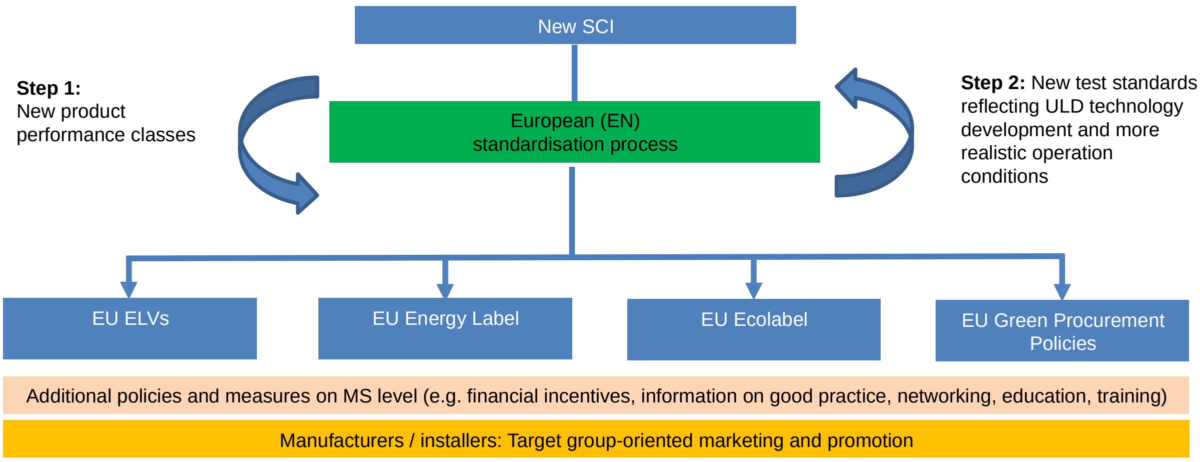

Figure 4: Recommended basic policy package for new SCI: Two-step approach

Source: Own illustration by the authors based on ULD project

The EU policy package for new SCI should be furthermore complemented by target group-oriented marketing and promotion by manufacturers and installers as well as adequate Member States policies (e.g. financial incentives for BAT or better, information on good practice, networking with energy auditors, installers and chimney sweepers, education, training/certification and public procurement rules).

Step 1: Improving product information for new SCI in the EU

MEPS and ELVs addressing the market access for new SCI in the EU

The cornerstone of any policy package with the aim to improve effectively the performance of appliances on the market is the implementation of mandatory minimum performance standards regulating the EU market access for new products. In the case of biomass solid fuel heating systems, MEPS (for energy efficiency) as well as emission limit values (ELVs) have to be regulated. Thereby, the EU Ecodesign process [6][7] already includes such “push measures” for new biomass solid fuel appliances. However, the demonstrated ULD technology would already provide a reference base for adjusting even more stringent requirements in a possible future review of the Ecodesign implementing measures.

Therefore, until stricter mandatory product performance criteria would be possible, improved product information (e.g. by labelling schemes, etc.) remains essential, as it will enable consumers to make more conscious purchase decisions towards the most innovative products. Additionally, improved EU product information could also provide the foundation e.g. for more ambitious emission-based policy packages by Member States as well as for target group-oriented marketing and promotion activities by manufacturers and installers.

EU Energy Labelling

Besides Ecodesign, the mandatory EU Energy Labelling is another powerful EU policy instrument to support an accelerated market transformation towards more energy efficient products on the European market. For biomass solid fuel SCI, the market transformation has to be supported towards emission reduction at the same time. However, the forthcoming current EU Energy Labelling approach with focus only on energy efficiency [6][7], will not be sufficient to provide a distinction between current BAT products and ULD technologies regarding their co-benefits, because for these high-end products there is no more a systematic direct correlation between better energy efficiency and much lower emissions. For example, the very best BAT boilers (with condensing technology) can achieve already the upper technical limit for energy efficiency, but not the same low emission levels as ULD products at the same time. In order to make this difference prominently visible to the end-user and to reflect adequately these additional co-benefits, dedicated new information requirements on the product label itself are needed. For this purpose, it is recommended to show on a future mandatory EU Energy label also easily comprehensible information regarding PM emissions in order to address at least the most health relevant emission category.

EU Ecolabelling

The EU Ecolabel - the voluntary environment endorsement label of the European Commission - can be an effective instrument for an additional promotion and faster market diffusion of very innovative technologies. “Commission Decision 2014/314/EU establishing the criteria for the award of the EU Ecolabel for water-based heaters”, covering also solid fuel boilers, has been adopted on 28 May 2014. After publication in the Official Journal of the EU in June 2014 it entered into force immediately and is subsequently applicable for the next 4 years [12]. It includes ambitious efficiency and emission requirements for biomass SCI and might already promote current BAT after the registration of the first products. Nevertheless, compared to the performance level of the new ULD technology, there would even remain a potential for more demanding requirements in a next label version in order to support the most innovative technology.

Revision of current product standards

In order to further promote ULD technologies, EU research programs for new or further revised product and test standards should be supported, including the respective tenders for CEN for an accelerated implementation of the new standards. Currently, for solid fuel boilers (indirect heaters) the highest product performance class defined in the applicable EN standard does not allow to make a distinction between good, very good and the best technologies already on the market. For example, the majority of wood pellet boilers put on the market in 2013 already achieved the highest class requirements. Therefore, the introduction of new classes should be considered, as especially a class only achievable by the most advanced appliances would allow manufacturers to claim a distinct level of product performance based on official and generally accepted technical documents. This could encourage manufacturers to foster innovation even before other (mandatory) requirements will come into force or will be reviewed. For solid fuel local room heaters (direct heaters), the current standards do not include any performance classes at all, which should be also addressed in future standards or revisions.

Basic financial incentives addressing new SCI on the market

Such as many new approaches, ULD technologies face initially a financial barrier due to the higher upfront investment costs compared to current BAT solid biomass and especially oil and gas heating technologies on the EU market. Therefore, financial incentives can be an important argument for customers to opt for innovative, but initially more expensive ultra low emission biomass technology instead of other products fulfilling just the required minimum performance criteria. However, tax rebates, subsidies, or other financial incentives to support products directly can currently not be implemented or prescribed by the EU, as such measures are only possible on Member State level.

Also other current EU instruments like the Structural Funds of the EC (DG REGIO) cannot be used for such specific purposes, because no direct support of end-users is allowed. The European Investment Bank (EIB) is considering programs for sustainability measures in the building stock (e.g. social housing or on district level), but only with a holistic approach and not for specific building technologies like heating systems. Consequently, existing examples for specific financial incentives in the context of SCI can only be found on EU Member State level (e.g. BAFA scheme in Germany, CIDD/crédit d'impôt développement durable in France or the Voivodeship Fund for Environment Protection in Poland). Besides incentive programs by EU Member States, there are also numerous other existing incentives for biomass heating technologies implemented on regional or municipal level across Europe.

Thus, it is recommended to take improved and synergetic multi-level governance action on EU, Member State and regional level (including e.g. INEA, Covenant of Mayors, etc.) to revise existing financial incentive schemes and to implement new ones, respectively based on the improved product information proposed in Step 1 for new SCI. Depending on the economic situation of the MS, at first glance the implementation of such incentives might seem to be challenging, but many other possible positive long-term effects (such as fostering regional investments, local creation of new ‘green’ jobs in the forestry sector or in manufacturing industry/SME, related fuel cost savings, increased security of energy supply as well as reduced air-quality related negative health impacts, etc.) need also to be taken into account. By this means, the whole society will benefit from reducing energy consumption and emissions, in particular in terms of lower energy and health costs, but e.g. also due to avoided possible Ambient Air Quality Directive related monetary penalties. Therefore public authorities on all levels should be highly interested in allocating money for financial incentives programmes for innovative new technologies. All potential new incentive schemes should thereby be always complemented by information on good practice, networking with energy auditors, installers as well as education, training and public procurement rules on Member State and local/regional level.

Promotion and marketing activities by manufacturers and installers

Finally, it should not be underestimated that manufacturers and installers and their associations have an important role in promoting especially highly efficient technology with ultra low emissions and to show the additional co-benefits of such products. For this purpose, they can perform target group-oriented marketing campaigns to highlight the general advantages, the environmental benefits as well as other added value aspects of the innovative technology.

Step 2: Addressing real-life product performance of new SCI on the market

Comprehensive revision of product and test standards

- Efficiency and especially emissions of heating systems are in reality different than measured according to current product type testing approaches, because operation patterns under real-life conditions are deviating from synthetic benchmarks. In particular, the actual performance depends also on the entire heating system as well as user behaviour. Therefore major revisions of product and test standards are recommended, in order to include much more realistic test requirements.

Update of the entire specific policy package for new SCI

As soon as the relevant product and test standards have been revised, all existing as well as new policies and measures of the policy package addressing new SCI will have to be updated accordingly for consistency. As the new product and test standards could focus in particular on the most health-relevant emissions like the PM_{10} or $PM_{2.5}$ particle fractions, also a more specific policy development would be possible afterwards. Based on the policy instruments suggested in Step 2 for new installations, Figure 5 presents an overview of the current specific EU policy package for new SCI and the recommended policy evolution.

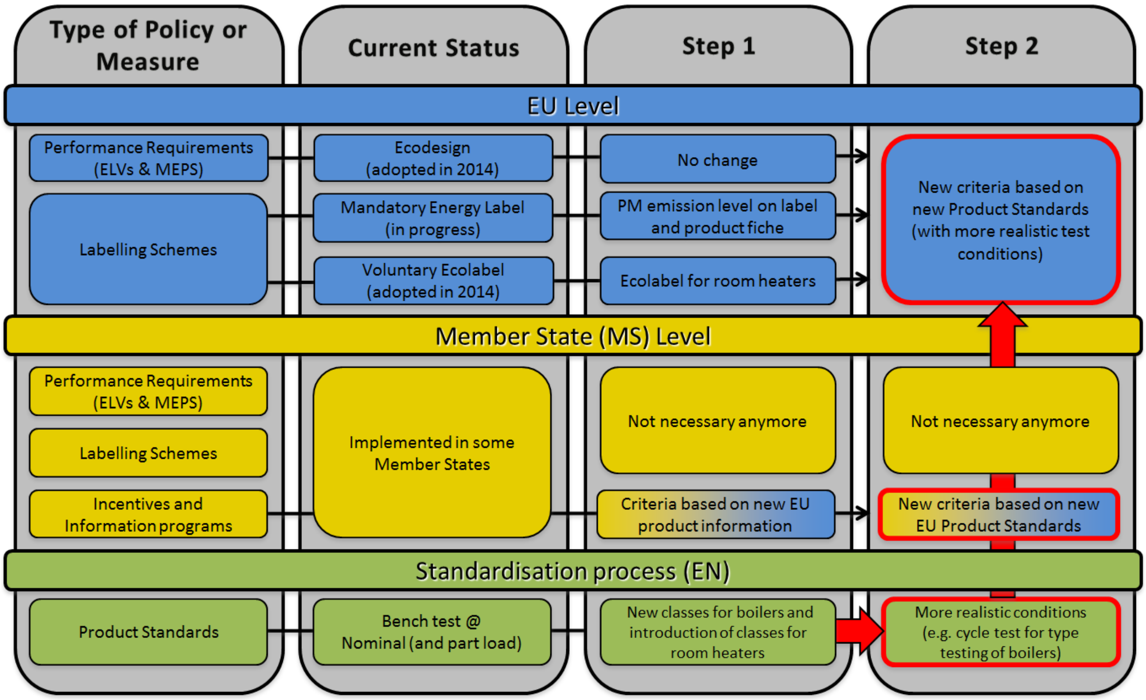

Figure 5: Recommended evolution of the policy package for new solid biomass SCI: Step 2

Source: Own illustration by the authors based on ULD project

Complementary recommended policy package for existing SCI

General policy package approach

The performed impact assessment scenario calculations highlighted the urgent need to address not only the market and therefore solely new products, but especially also the existing stock of old and poorly performing appliances. Thus, it is recommended to introduce a complementary policy package specifically for existing SCI (to be applied in synergy with the recommended measures for new SCI), which will accelerate significantly the early exchange of existing out-dated installations compared to the autonomous replacement process induced solely by the technical product lifetime.

This complementary policy package for existing SCI in the stock should include:

(1) Regulation

Minimum performance requirements addressing specifically existing SCI in the stock

Analyses of different international voluntary change-out initiatives for solid fuel heating system have principally confirmed their general effectiveness and benefits regarding efficiency gains and emission reductions [2]. However it was also revealed that the long average service life of such appliances - once installed – is a relevant limitation for voluntary approaches.

In order to tackle this limitation the EU or Member States shall implement – synergetic to the before described measures for new SCI - also specific additional mandatory requirements for existing SCI, which ensure an effective accelerated exchange of old and poor performing existing installations with much better performing new biomass solid fuel systems. In any case, if regulatory restrictions do not yet allow such requirements directly on EU-level, the EU should at least encourage the implementation on Member State level.

For such future regulations, also experiences of the implementation of the German 1. BimSchV [13] emission regulation (with its ambitious 2nd tier coming into force in 2015) should be taken into account, which is so far the only national policy of this kind in the EU:

- For solid fuel indirect heaters (boilers): Introduction of operation performance requirements with special focus also on PM emissions as well as periodical on-site inspections, which are e.g. performed by chimney sweepers or other responsible authorities.
- For solid fuel direct heaters (local room heaters): The regulation shall be based on a type testing approach, but according to new or revised EN standards as described in Step 1 for new SCI.
- The regulations shall include general mandatory replacement requirements for existing installations not complying with the new standards.

Thereby regulation approaches shall be preferred, with the target of an overall performance improvement of the whole stock of installed biomass solid fuel heating systems by means of ultra low emission biomass technology so that the general or temporary banning of biomass solid fuel usage (e.g. during periods with PM values exceeding the limits of EU Directive 2008/50/EC) can be avoided to ensure security of energy and heating supply.

Although the implementation of such regulation is challenging in certain aspects (on-site inspections need e.g. adequate training of the chimney sweepers as well as special equipment), only such mandatory policies can ensure that inefficient appliances with high emissions will be actually removed much earlier from the stock and would be consequently replaced in any case by better performing products, as consequence of minimum requirements in the basic policy package for new SCI addressing the market [2]. In this context, it is also recommended to improve the general usage of adequate market and stock surveillance as well as the usage of respective product databases on EU and Member State level in order to have always access to up-to-date and reliable data for more specific policies [14]. Thereby, experiences from existing databases (such as e.g. the German HKI compliance database for SCI, http://cert.hki-online.de/) should be taken into account.

Fuel quality

As fuel quality has been identified as an essential influencing factor for the real-life performance of solid fuel SCI, it is recommended to include also this parameter in specific regulatory measures. For this purpose, the quality of the fuel should be especially controlled and regulated at the point of sale, what is mainly of relevance for fuels, which are sold on the market in large quantities, e.g. by bulk wholesalers. In this context, a reliable certification system for the suppliers and a control mechanism for the fuel stock would be required. In case of specific biomass solid fuels, where a significant share is typically originating from smaller own resources of the SCI users (e.g. wood logs, saw dust, wood chips from private forest estates or related timber industries), especially good practice rules should be applied. Considering this, all measures to exclude fuels of inadequate quality would have immediate and measureable positive effects on product performance and the environment.

(2) Cumulative financial incentives addressing existing SCI in the stock

Besides the long service life of installed solid fuel heating systems, analyses of different international change-out initiatives have revealed the costs of the best technologies as another relevant limitation of any voluntary exchange approach [2]. In order to tackle this barrier and to address remaining SCI in the stock, which comply with mandatory performance requirements for existing installations as described in (1), but whose performance is clearly below BAT level of the market, additional financial incentives shall be implemented as "pull" mechanism to support a voluntary early replacement. Thereby, the incentive for early replacement shall be cumulative to basic incentives granted for new products (see section "recommended basic policy package for new SCI"), supporting in particular the purchase of the most innovative new products with significantly better performance levels than Ecodesign / MEPS minimum requirements as substitute (Figure 6).

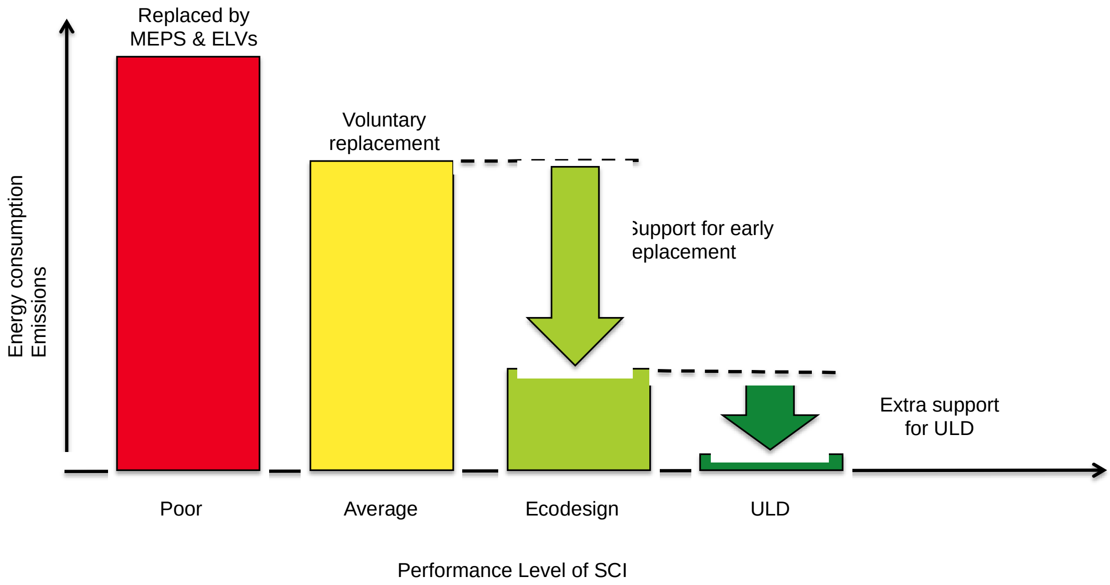

Figure 6: Cumulative financial incentives for early replacement with ULD as substitute

Source: Own illustration by the authors based on ULD project

However, also financial incentives for early replacement can currently not be implemented or prescribed directly by the EU. Consequently, examples for such complementary financial incentive schemes to replace old SCI by much better performing new ones can only be found on Member States level (e.g. Incentive for replacement of old installations in Austria, CIDD in France, Voivodeship Fund for Environmental Protection in Poland).

(3) Information, education, training, networking and promotion

To complement the measures described in (1) and (2) for existing SCI in the stock, it is recommended that chimney sweepers (or other responsible authorities) also check the entire heating installation and the quality of fuel on a regular basis. Furthermore, for biomass solid fuel SCI, improper operation is another relevant parameter influencing negatively the real-life performance. For this purpose, extensive good practice information programs - beyond printed information at the point of sale - should be provided to the owners and operators of all installed systems. Thereby, training could be also realized during the regular and official chimney sweeper visits in combination with the provision of advanced information brochures like e.g. the "Low emission operation manual for chimney stoves" developed in the ERA-NET "FutureBioTec" project [15]. Again, manufacturers and installers and their associations have also a strong role in promoting the exchange of inefficient existing SCI in the stock. They could perform target group-oriented marketing campaigns (e.g. in the context of regular maintenance procedures) to highlight the need for improvements and the innovative character, the environmental co-benefits as well as further advantages of exchanging existing old appliances with highly efficient new products.

Summary and Outlook

This paper presented results from impact assessment scenario calculations for technical energy efficiency and emission reduction potentials as well as respective policy options and recommendations to support highly efficient and ultra low emission small-scale residential biomass heating systems in Europe with the target to harness the significant improvement potentials as far and as soon as possible.

For this purpose, the recommended basic policy package for new SCI to be put on the EU market consists of a two-step approach and aims at supplementing the current and already forthcoming policies addressing new SCI in Europe. Following stakeholder feedback, the realization of the recommended Step 1 for new SCI should be possible in short- to medium term, e.g. following a respective EU Ecodesign and labelling implementation. In this context, the European standardisation processes might require more time than other parts of Step 1, as new testing methods have to be agreed and approved especially with respect to emissions. The same is also valid in Step 2 in the new SCI policy package, where the development of essentially new and more realistic testing methods (considering real-life operation) as well as the subsequent adaptation of all relevant regulations could require more time. Therefore, based on the necessary research and regulatory process, Step 2 should be envisaged according to stakeholder feedback in a medium to long-term perspective.

The second recommended and complementary policy package for existing SCI is intended to support in particular the early substitution of poorly performing existing solid fuel SCI in the stock with significantly improved new heating systems, as the implementation of ambitious replacement programs is the most promising approach to achieve energy efficiency improvements as well as large and rapid emission reductions at the same time [3]. Thereby reliable databases for new products would be very helpful for consumers and - in combination with registers of already installed SCI - an essential precondition for policy makers to develop replacement approaches [14]. As the EU can currently only encourage Member States to implement such concrete measures due to regulatory restrictions, a better harmonisation or even completely new and more holistic policy instruments on European Level would be needed.

Finally, in the context of both closely related policy package parts for new and existing SCI, two instruments are considered as most important by involved stakeholders: Mandatory performance ("Push") requirements to address energy efficiency and emissions of heating appliances directly and effectively as well as financial incentives to foster ("Pull") a much faster market and stock transformation. However, due to the existence of regulatory restrictions hindering currently the implementation of certain instruments on EU-level, in both SCI policy packages further and advanced information, promotion, networking, education and training/certification programs remain also essential in order to influence buying decisions of consumers and to reduce emissions in real-life operation by addressing user behaviour as well as the quality of fuels.

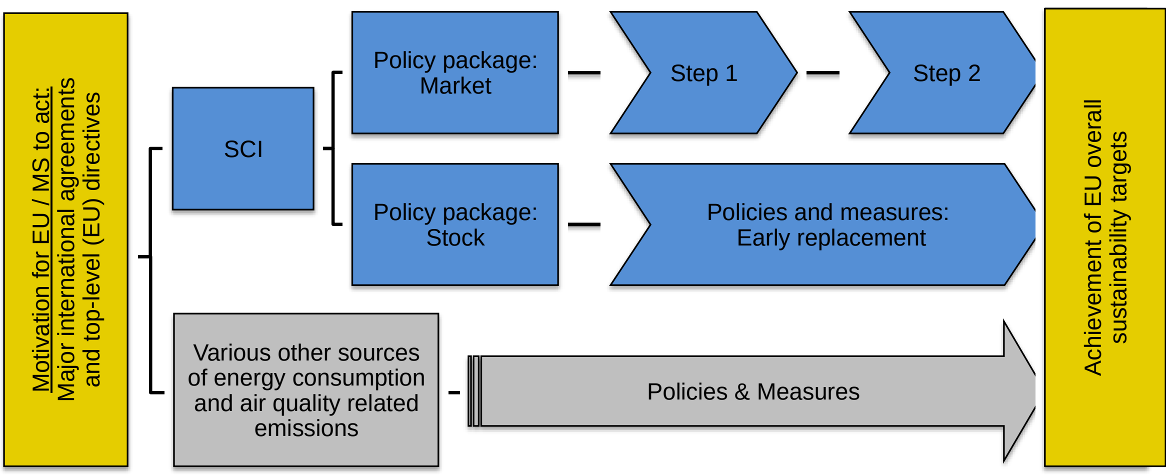

Figure 7: Context of the EU-UltraLowDust policy packages for SCI

Source: Own illustration by the authors based on ULD project

Taking into account the policy recommendations developed in the ULD project and discussions with several national / EU experts and authorities for solid fuel SCI as well as industry representatives, it can be stated that the implementation of the proposed policy packages is considered as difficult in certain aspects, but yet feasible. Substantial resources would be required but e.g. the EU multiannual financial framework, Horizon2020 or INEA/CEF may provide scientific and financial starting points. Based on this, incentives as well as cohesion in building codes will further support innovative technologies. EU Structural Funds can be used e.g. to address major regional energy or air quality issues and also to support the new Member States, where economic and social aspects have to be taken specifically into account.

Depending on possible tight economic situations in some MS, at first glance the implementation of ambitious measures might seem to be challenging, but many possible positive long-term effects (such as fostering EU-wide regional innovation and investments, local creation of new jobs, related fuel cost savings, increased security of energy supply as well as reduced air-quality related health costs, etc.) need also to be taken seriously into account. Especially in this context, it has to be stressed again that in most parts of Europe solid biomass is also the cheapest and most easily available type of fuel for heating purposes and it is therefore the basis for a very secure and economical type of heating systems. With this in mind, the ULD project demonstrated very promising technologies with high efficiencies and ultra-low emissions for boilers and stoves, which show the enormous general improvement potentials of an encouraged sustainable solid biomass heating strategy in Europe. In combination with adequate policy packages such innovative technology can also provide major co-benefits and contributions to achieve the declared EU-wide overall sustainability targets (Figure 7).

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Penetration of residential heating equipment and the energy mix: evidence from a survey on Italian installers

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Abstract

Policies for the promotion of energy efficiency and renewable energy sources have played an increasingly important role in investment decisions on heating and cooling equipment, in addition to market, technology, and infrastructural drivers.

Monitoring adoption of available technologies may serve as a useful tool for both market players – manufacturers, energy utilities etc. – and policy makers to assess potential penetration in relevant market segments as well as the cost-effectiveness of policies.

This paper illustrates a monitoring exercise carried out – on a yearly basis – on 2011-2013 with a focus on the adoption of residential heating and cooling technologies in Italy. The exercise consisted in surveying around 800 installer firms annually, with the aim of obtaining a representative sample of the Italian market according to climate, wealth, access to natural gas, and urban density. Partial and full replacement trends were investigated in each relevant market segment, including independent and collective heating systems, newly built and existing buildings, and presence of a natural gas network.

Results suggest that the adoption of efficient and renewable technologies, driven by both market and regulatory forces, has started to affect the technology mix significantly. Yet, preliminary estimates indicate that the energy mix has been affected by technology adoption trends only to a limited extent. As far as the demand for natural gas is concerned, it may be expected that drivers stronger than the technology mix have affected the energy consumption of households so far.

1 - Introduction

The EU climate policy – passed by the EU Council in March 2007 [1] – requires Member States to promote energy efficient technologies as well as technologies that use renewable energy sources, with the ultimate objective of achieving decarbonisation goals. Climate policy measures – establishing obligations and standards, financial support schemes, labelling schemes, and aiming to empower the consumer – apply not only to electricity generation and transport, but also to heating and cooling.

In fact, both in EU and Italy, energy use for heating and cooling accounts for no less than 80% of household consumption [2] [3]. Natural gas is the main energy source for heating in the EU. In Italy, natural gas accounts for 67% of consumption for heating and cooling [3] – this share being one of the highest in the EU.

Importantly, the International Energy Agency [4] has recently called for improved data collection and analysis that “will help Government and other stakeholders to better track energy efficiency developments, which will in turn support stronger policy design and better identification of market opportunities”. With a closer focus on end users, Eurostat [5] states that “the information needs derived from the new energy policies of the EU make it necessary to get a deeper knowledge of the end-consumer sectors”.

This paper contributes to reply to this challenge by addressing the impact of policy measures on the heating and cooling generation mix of the household sector, as well as the impact of other drivers, such as technological progress, market prices (including fuel prices), socio-economic changes, and the setting up of energy infrastructure.

The paper reports on the results of a study whose first and main objective is to assess changes in the technology mix for heating and cooling generation in Italy through the monitoring of installation and replacement trends of relevant equipment. The study consists in surveying a sample of installer firms operating across the country over the years 2011, 2012, and 2013.

Monitoring the technology mix for heating and cooling surely meets the need for improved data on the part of market players such as manufacturers, energy utilities, energy saving companies, and installer firms. Not only are data on the sales of heating and cooling technologies key for businesses, but market players such as manufacturers and utilities are also increasingly interested in how technologies combine in complex systems, involving building insulation, heat and power generation and distribution, control of ambient temperature, metering and monitoring of consumption, etc. Market players may also want to assess competition among technologies in order to identify marketing opportunities in specific segments, as well as the potential for diffusion of new technologies such as hybrid systems[1]. Institutional bodies such as antitrust authorities may be willing to undertake similar analyses, with the aim of assessing competition and possibly regulating the industry [6].

Data on the technology mix may represent an important input to feed energy consumption models – or any other estimation exercise – as well as to validate the results of other surveys or integrate administrative datasets. Key to the activity of network operators and energy suppliers is estimating and forecasting how changes such as those in the technology mix for heating and cooling may affect the demand for natural gas or electricity [7]. Governmental bodies in charge of implementing energy and climate policies may need data on the flows of heating and cooling technologies to track renewable energy consumption and the progress towards mandatory goals set at the EU level and – more generally – to assess the effectiveness of promotion policies.

The paper is organised as follows. Section 2 presents an overview of relevant EU and Italian legislation and policy measures, which may affect the residential technology mix for heating and cooling. Section 3 outlines the survey's methodology, with reference to sampling, drafting the questionnaires, administering them, and processing the data. Section 4 illustrates the results, respectively for the independent heating systems segment and the collective heating systems one. Section 5 presents some preliminary elaborations concerning the impact of technology switching on the demand for natural gas – Italy's main energy source for households. Finally, section 6 provides some concluding remarks and outlines the main needs for further research.

2 - Relevant legislation and measures at EU and Italy level

Most rules relevant to heating and cooling in the residential sector may be found in five EU directives.

Directive 2012/27/EU [8] – the Energy Efficiency Directive (EED) – establishes a common framework for energy efficiency in the EU, with the primary objective of ensuring the achievement of the Union's 2020 indicative target, i.e. primary energy consumption to be 20% lower than projections made in 2007. EED also sets absolute targets for both primary and final consumption, and requires each member state to set an indicative national target consistent with such references, through a national action plan. Specific to heating and cooling consumption in the residential sector, EED requires Member States to assess the potential for the application of high-efficiency cogeneration and efficient district heating and cooling and take adequate measures for the development of the necessary infrastructure. Furthermore, EED requires Member States to remove incentives in transmission and distribution tariffs that are detrimental to energy efficiency in the supply of electricity. Finally, it mandates certification schemes for installers at Member State level.

The key legislative reference for the promotion of renewable energy sources (RES), including energy from RES in final consumption for heating and cooling, is Directive 2009/28/EC [9]. The RES Directive sets a mandatory target for each Member State, and requires such target to be allocated to electricity, heating and cooling, and transport through a national action plan. It mandates certification schemes for installers at Member State level, and establishes rules to account for renewable energy generated by heat pumps.

Directive 2010/31/EU [10], known as the Energy Performance of Buildings Directive (EPBD), lays down requirements concerning – amongst other aspects – the energy performance of new buildings and new building units, the installation, replacement and upgrading of "technical building systems"

[1] In this paper a hybrid heating system is referred to as a system that combines a furnace with a heat pump, and it is generally designed to alternate between furnace (colder weather conditions) and heat pump (milder weather conditions).

(including space heating and cooling, and sanitary hot water generators), and finally the inspections of space heating and air conditioning systems.

The Energy Related Products – or Ecodesign – Directive (Directive 2009/125/EC) and the Energy Labelling Directive (Directive 2010/30/EU) [11] [12], together with their implementing regulations, respectively set minimum design specifications for space heating and sanitary hot water systems and a EU-wide labelling scheme for heating and cooling equipment. These changes will become mandatory from September 2015.

In Italy, standards for the energy performance of new buildings have been in place since the 1970s, but these were tightened by primary legislation implementing the EPBD [13]. RES obligations have applied to sanitary hot water at national level since March 2011[2], while these have applied to the joint consumption for space heating and sanitary hot water since May 2012 [14], meaning that an obligation has been in place since that time on newly issued building licenses.

National support to efficient and RES-based technologies in the residential sector has been carried out mostly through income tax rebates, amounting to 55% of the investment cost [15][3]. Other schemes have supported investment by households marginally, such as a white certificate scheme (in force since 2005) [16], or these have proven scarcely effective, such as a hybrid feed-in-tariff and investment support scheme known as the "Conto termico" (in force since 2013) [17]. Support has been carried out through taxation too, such as in the case of reduced VAT for biomass and electricity, and reduced excise duties for biomass [18]. Finally, transposition of EED into national legislation included establishing dedicated non-progressive electricity tariffs for heat pumps used by households as the only system for space heating, though such regime has been passed as a transitional one [17][4].

3 - Sample, questionnaire and survey design and administration

3.1 - Scope of the work

Most surveys and literature on technology diffusion in the residential sector focus on lighting and electrical appliances and systems, and the respective impact on electricity consumption, through investigation of households (see for instance [19] and [20]).

A business survey has the main advantage to ensure good coverage of the market at relatively low cost and reduced delays, as compared to a household survey. On the other hand, such an exercise has the disadvantage of hardly resulting in full characterization of the context where an energy efficient or renewable intervention took place, as it is instead achievable through a survey on households.

The author is aware of few business surveys focusing on installers, such as the survey conducted by the French research institute CEREN [21] [22][5].

Three runs of the survey were carried out in the period 2012-2014, each one focusing on installation works completed during the previous year, and each one labelled accordingly as "survey2011", "survey2012", and "survey2013".

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[2] These have been in place for longer in some of Italy's regions, especially in the North.

[3] Support level was increased to 65% in June 2013.

[4] A reform of network tariffs is currently under discussion, which should result in phasing out their present progressive structure. Amongst other effects, progressive tariffs discourage the use of high-efficiency electrical equipment such as heat pumps.

[5] The ultimate objective of the CEREN survey is to feed a monitoring work on the stock of heating systems and the respective consumption in the residential sector. The survey concerns centralised individual systems and involves around 250 installers on a yearly basis. The outcome of the survey is extrapolated data on: 1) the number of dwellings where a heating system was installed; 2) the number of dwellings where installation of a heating system took place for the first time; 3) the number of dwellings where the heating equipment was replaced without changing energy source; and 4) the number of dwellings where the heating equipment was replaced with new equipment fuelled by a different energy source. CEREN survey does not cover either collective (multi-dwelling) systems or individual local (one-room) systems, and it focuses on existing buildings only. Other specific surveys are implemented to gather such data.

The target of the survey were installers of heating and cooling generation equipment operating in Italy having installed at least one such system in residential units during the year under investigation. Surveyed technologies are listed below.

- Condensing gas boiler
- Non-condensing gas boiler
- Combined gas boiler and solar panel system
- Gasoil boiler
- Condensing liquefied petroleum gas (LPG) boiler
- Non-condensing LPG boiler
- Air-to-water heat pump and water-to-water heat pump
- Air-to-air heat pump (independent heating system only)
- Biomass (pellet, wood) stove or fireplace stove (independent heating system only)
- Biomass (pellet, wood) boiler
- Solar thermal panels

3.2 – Sample design

The population of installers of heating and cooling equipment includes the firms identified by NACE code 43.22[6]. A minimum target was set of 800 valid interviews – corresponding to a 1.2% share fo the population of installers[7]. This target was further broken down into one target for interviews concerning works in the "independent heating systems"[8] segment (700 valid interviews) and one for interviews in the "collective heating systems"[9] segment (100 valid interviews). This split was carried out with the aim to reflect the higher share of the independent segment, as opposed to the collective one, in terms of number of heating systems sold and installed, while at the same time ensuring that a satisfactory number of interviews be carried out for the collective segment. Finally, geographical allocation of interviews was carried out.

For the independent segment, all 109 Italian provinces were classified according to four indicators obtained from administrative data, i.e. prevailing climatic zone (Figure 1), per-capita income, penetration of the gas network, and urban density. These should explain the following drivers of the technology and energy mix for heating and cooling in Italy's residential sector[10].

- Climate
- Wealth
- Access to natural gas
- Level of urbanisation

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[6] At national level, the Italian agency for statistics – Istat – uses both the 43.22 code and the sub-code 43.22.01.

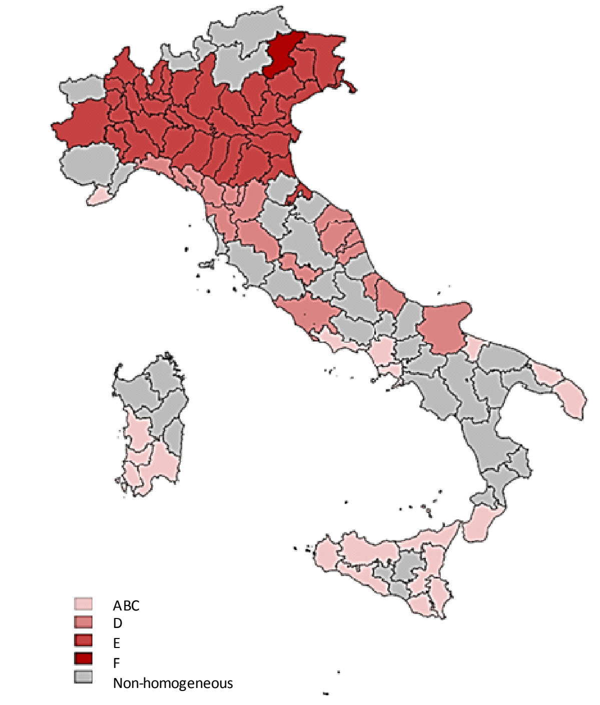
[7] This was the case for survey2012 and survey2013, while a minimum target of 400 interviews was set for survey2011. Survey2011 may be considered as a pilot survey: some differences in the wording of questionnaires as well as in methodology make results only partially comparable to those obtained in subsequent years.

[8] Independent heating systems are heating systems that serve one dwelling.

[9] Collective heating are heating systems that serve more than one dwelling.

[10] The province represents Italy's closest administrative unit to functional urban areas for which data are available on the selected indicators.

Figure 1 – Distribution of Italian provinces according to climatic zones[11]



Source: Presidential Decree 412/93 (A,B and C zones aggregated by the author)

The definition of climatic zone applies to municipalities. As a consequence, provinces may be non-homogeneous with reference to climatic zones. Non-homogeneous provinces were therefore further divided, so that the number of units increased to 151.

Classification according to per-capita income was performed using latest available statistics published by Istat on per capita added value [23].

The natural gas network has an extensive penetration all over Italy, with the exception of Sardinia, where no such infrastructure is in place. Nevertheless, differences may be found as to the extent to which natural gas can be accessed by citizens, firms, and factories: lower penetration is found in mountaineous areas as well as in islands. A ratio was calculated to estimate the penetration of the gas network using available data on gas delivery points [24] and number of families [25].

Finally, urban density was estimated as the ratio between the number of dwellings in each province and the numer of buildings whose main use is residential, according to Istat's 2011 census on population [26].

Following the characterisation of Italian provinces, these were grouped into homogeneous classes through a non-hierarchical clustering method. The *k-means* method was chosen to minimise the deviation within the classes and to maximise the deviation between one class and another, according to the four drivers illustrated above. The distance between the provinces and the centres was calculated using the Euclidean distance method after standardisation of the values related to each of the four drivers.

The number of classes was set to 21 – class 21 being Sardinia[12] – with the aim of obtaining a significant number of interviews per class, while at the same time ensuring a large enough sample for each class.

[11] Italy's municipalities are allocated by the law to 6 climatic zones, A being the one with the warmest climate (measured through heating degree-days) and F being the one with the coldest climate. Zones A and B account for a very low number of municipalities, thus the were grouped with zone C for the purposes of this study.

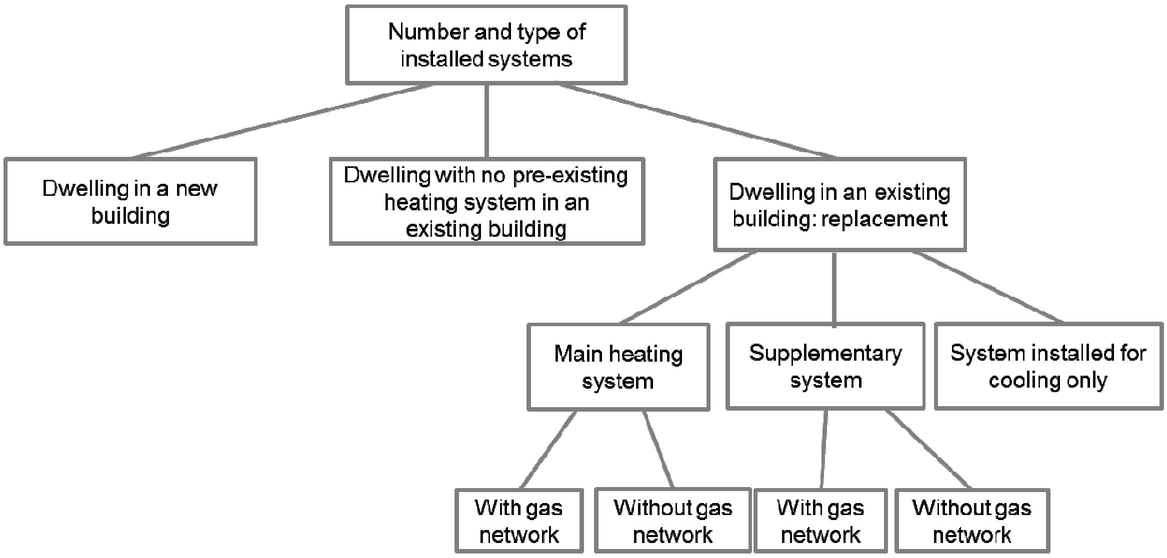
As a third step, interviews were allocated to each class using the number of installers in each class as a proxy of the class' market share[13].

Interviews targeting the collective segment were more simply allocated to urban areas featuring the highest shares of collective heating systems.

3.3 - Questionnaire design

Two different questionnaires were designed for the independent and the collective segments. These questionnaires share, however, a similar structure: core to the questionnaire is a set of questions on the type and number of installed and replaced heating and cooling generators, according to the segmentation scheme illustrated in Figure 2.

Figure 2 – Segmentation of the residential segment for questionnaire design



Source: author's analysis

The first section of the questionnaires collects information and data on the firm's profile.

The respondent is required to fill in the second section of the questionnaire with data on the type and number of installed systems during the year under investigation, with separate indication of the data concerning new and existing buildings. Also in this section a set of non-core questions were asked, concerning the generation of sanitary hot water (survey2013), the installation of efficient heat distribution systems (survey2012), the installation of devices for controlling the system and metering/monitoring consumption (survey2012 and survey2013), and the combination of heat pumps with photovoltaic generation systems (survey 2013).

The third section is designed to collect data on the number and type of heating and cooling systems replaced, for all newly installed systems in existing buildings where a heating system was in place before the installation work. Full (or almost full) substitution is investigated – as opposed to supplementing the main heating system – for technologies that are known to serve mostly as local systems, i.e. air-to-air heat pumps (split systems) and biomass-fuelled stoves and fireplace stoves[14]. Finally, for both main and supplementary systems, the question was asked – if relevant – of whether installation took place in an area with or without the gas network.

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[12] Sardinia is unique in Italy for its lack of a gas network.

[13] The underlying assumption is that no relevant difference exists in the number of equipment installed by installers working in different areas of the country.

[14] All other technologies are assumed to be installed as the main heating system, thus their possible use as supplementary systems is not investigated through the survey. The only exception to this assumption is solar thermal panels, for which the opposite assumption holds true, i.e. being used as a supplementary technology in all cases.

The fourth and the fifth sections address strengths and weaknesses of each technology and investigate the installers' mid-term expectations on the market performance of each technology relative to all others.

3.4 - Surveying activities

All runs of the survey were partially carried out through face-to-face interviews – amounting to around 20% of all interviews in survey2013 – conducted by the team involved in designing and managing the survey, and in processing data. Printed questionnaires were used to this end. The interviewees were selected randomly at trade fairs of the heating and cooling industry. Therefore, interviewees did not know the questionnaire content before the interview. Consistency check was inherent in the interview: the interviewers used data gathered in section 1 (number and type of installed equipment) to guide interviewees in answering section 2 (number and type of replaced equipment).

The majority of interviews were then carried out through computer-assisted web and telephone interviewing techniques by experienced and trained staff of a market research firm. In both cases, consistency check was embedded in the web-based questionnaires. Filters to non-relevant questions were also active in both cases. Self-managed questionnaires accessed through a dedicated website allowed the respondent to complete the questionnaire within 3-4 weeks (either at one time or in subsequent steps). A glossary and online guidelines were provided in this case.

A significant number of questionnaires was administered via email in survey2013 – amounting to around 20% of the total – thanks to the support of an official network of installer firms. In this case, guidelines were also attached to the questionnaire, and a help service was provided by trained staff of the partner installer network.

After data collection, further consistency checks were carried out, together with checks on outlier data. Follow-up calls were performed to further investigate these cases.

3.5 - Extrapolation of sample data

After sample data were entered and checked, these were extrapolated to the national level, by multiplying the average results per installer firm in each class by the respective number of installers. Average results were calculated by adjusting the results of each class to those of all other classes: the higher the number of interviews in a given class, and the higher the distance between such class and the others, the lower the adjustment. Adjusting results helped addressing potential bias deriving from the low number of interviews in some classes.

At a subsequent stage, constraints were imposed onto the resulting estimates, with the aim of reflecting the actual technology mix of newly installed equipment, and the actual allocation of flows of new heating and cooling systems in new buildings and in existing ones. Administrative data were mostly used to this end[15]. Using actual sale data and actual shares for new and existing buildings as constraints to the extrapolation process helped correcting potential bias in the sample[16].

Data validation was carried out to the extent possible, i.e. where data were available from administrative sources and other surveys. This is the case for few specific aspects, such as the use of heat pumps either as a cooling-only system or as a heating and cooling system (a main or supplementary one) [27].

[15] Manufacturers associations' survey data on sales on the domestic market were used for fossil-fuelled boilers, heat pumps and district heating systems. In the case of biomass systems, estimates were used that are made available to the public by the relevant associations. Based on such data, installation flows in the residential sector were estimated, again through the support of manufacturers associations. The weight of the new buildings segment and the existing buildings one was estimated using administrative and literature data on building licences and the turnover of the existing stock of systems respectively.

[16] A self-selection bias possibly affects the sample in all runs of the survey, eventually leading to a technology mix that is unbalanced towards efficient and renewable technologies.

4 - Results

4.1 – An introduction to the Italian market of heating and cooling equipment

Sales of heating and cooling generation equipment in Italy account for more than 1.7 million pieces yearly – this estimate including air-source heat pumps used for cooling only. Unlike several other EU countries – where the number of condensing boilers outweighs that of inefficient ones – conventional boilers represent the leading technology for heating. A major share of this kind of equipment is manufactured in Italy, and mostly sold in the national market. As far as heat pumps are concerned, air-to-air heat pumps are almost entirely imported, while an industry for manufacturing air-to-water heat pumps is rather strong in the country – most production being exported to the EU and internationally. Similarly, Italy is one of the world's leaders in the market for biomass stoves and fireplaces and most pieces sold in Italy are produced nationally. However, Italy heavily relies on imported biomass (especially pellet) from centre-European countries such as Austria as well as east-European ones.

4.2 – Coverage and description of the sample

Overall, 871 interviews were carried out in survey2013, while 823 were carried out in survey2012 and 463 in survey2011[17]. Valid interviews amount to 98% in survey2013[18]: these feature at least information on the firm's profile and data on the number and type of heating and cooling systems installed and replaced in each sub-segment – new, existing, main heating system, supplementary system, with gas network, without gas network.

The number of surveyed heating and cooling systems amounts to around 25,000 in both 2012 and 2013, corresponding to around 1.4% of the estimated installation flows in the household sector, which remained almost stable in 2012-2013.

The distribution of interviewees according to the number of staff shows sufficient consistency with the industry's statistics: firms with a number of staff lower than 5 make up 70% of interviewees (the corresponding share for the whole population is 90%).

For most interviewees, installation, maintainance, and reparing represent a major share of turnover. On average, interviewees stated that installation covers 48% of their turnover, while maintainance and repairing cover 26% and 17% respectively (Figure 3). Other activities represent, on average, 10% of the turnover. For only 36 firms in the 2013 sample the share of turnover from other activities is higher than 50%.

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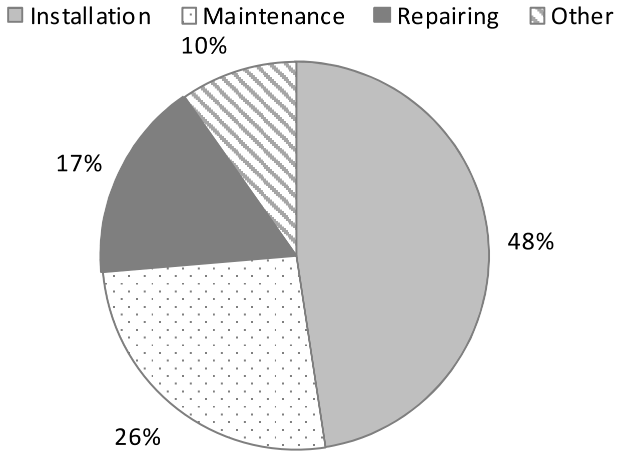
[17] The number of installers that took part in both survey2012 and survey2013 is 313. Out of these, 101 also took part in survey2011.

[18] At class level, targets were met in 15 out of 21 classes in survey2013 (independent segment), with lowest completion rate at 66%. Overperformance in some classes and underperformance in others were due to a no-refuse policy adopted during the final weeks of the survey to meet planned deadlines and address budget constraints. A similar decision was made for survey2012, based on the experience of very low response rates for survey2011. These appear to be in line with international experience [28].

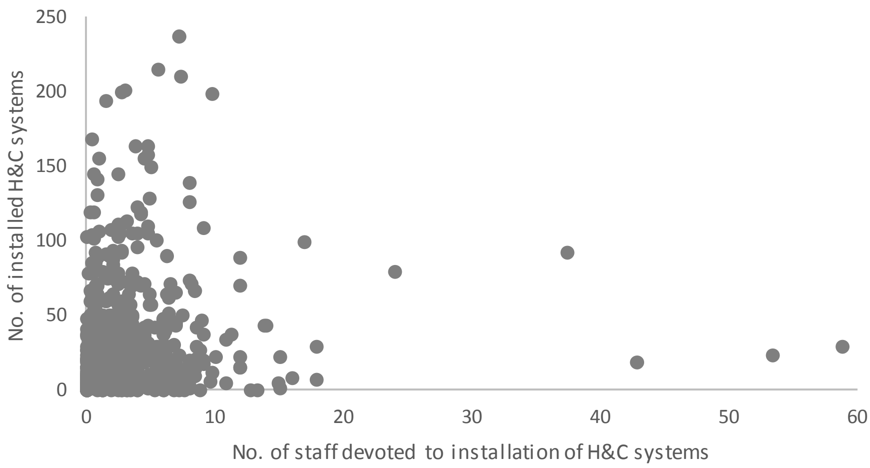
Figure 3 – Distribution of turnover by activity, 2013



Source: author's analysis on survey data

A low number of outliers results from the matching between the number of staff devoted to installation of heating and cooling equipment – owner, employees, other staff – and that of installed heating and cooling systems for survey2013, as shown in Figure 4.

Figure 4 – Number of staff and number of installed heating and cooling equipment, 2013



Source: author's analysis on survey data

The majority of installers in the sample did not work on one source or technology: only 225 interviewees answering survey2013 installed either fossil fuelled boilers only, heat pumps only, or biomass fuelled appliances only.

4.3 – Substitution grids

Extrapolated results of the survey at national level – limited to the existing buildings segment (this in turn represents more than 90% of the market) – are summarised in substitution grids, showing newly installed equipment in columns and replaced equipment in rows. Substitution grids describe penetration of technologies by allowing the user to measure the net balance between installed and replaced equipment and the share of occurrences when no switching takes place (a given technology replaces the same one). Moreover, these grids allow the user to detect competition among technologies, including assessing to what extent a given technology has replaced another one.

4.3.1 - Independent segment

With reference to 2013, Table 1 shows national installation flows in the independent segment (existing buildings), regardless of equipment use – either main heating system or supplementary system – and of the presence of a natural gas network.

Table 1 – Substitution in the independent segment, all heating systems, 2013 (number of systems)

	Installed systems											
Replaced/supplemented systems	Gas condensing	Gas non-condensing	Gas & Solar	Gasoil	LPG condensing	LPG non-condensing	air-water & water-water HP	air-air HP*	Biomass stoves	Biomass boilers	Solar thermal	TOTAL
Gas cond.	9 107	8 238	2 536	0	324	0	262	52 365	23 021	555	6 507	**102 915**
Gas non-condensing	147 170	345 688	22 297	14	1 771	2 024	1 078	172 442	181 754	3 580	5 794	**883 611**
Gasoil	8 007	4 845	1 625	1 609	3 492	3 696	77	6 685	26 222	3 409	847	**60 513**
LPG	2 269	1 691	519	277	8 539	22 078	183	10 842	92 405	5 403	3 182	**147 386**
HP	32	216	0	0	57	0	143	25 111	2 477	15	871	**28 922**
Biomass	41	69	52	42	0	0	28	1 465	24 699	1 749	1 387	**29 532**
Other	386	1 276	361	0	0	250	203	16 152	13 908	509	719	**33 764**
TOTAL	**167 011**	**362 022**	**27 391**	**1 942**	**14 182**	**28 049**	**1 973**	**285 061**	**364 486**	**15 220**	**19 307**	**1 286 643**

*Air-to-air heat pumps are excluded whose only use is cooling

Source: author's analysis on survey data and national sales data

The technology mix is largely etherogeneous in the independent segment: gas represents the most used source, while flows of new gasoil-fuelled and LPG-fuelled boilers are scarce. In order to assess the role of other technologies and better observe penetration trends, it is useful to consider main heating systems only: Table 2 refers again to Italy and to the independent segment (existing buildings), but flows have been cut off that concern systems installed to supplement existing ones, according to the extrapolated survey data.

Table 2 – Substitution in the independent segment, main heating systems, 2013 (number of systems)

	Installed systems										
Replaced systems	Gas condensing	Gas non-condensing	Gas & Solar	Gasoil	LPG condensing	LPG non-condensing	air-water & water-water HP	air-air HP	Biomass stoves	Biomass boilers	TOTAL
Gas cond.	9 107	8 238	2 536	0	324	0	262	1 035	3 004	555	**25 061**
Gas non-condensing	147 170	345 688	22 297	14	1 771	2 024	1 078	15 716	35 720	3 580	**575 058**
Gasoil	8 007	4 845	1 625	1 609	3 492	3 696	77	2 229	16 441	3 409	**45 430**
LPG	2 269	1 691	519	277	8 539	22 078	183	3 412	57 285	5 403	**101 654**
HP	32	216	0	0	57	0	143	15 267	0	15	**15 729**
Biomass	41	69	52	42	0	0	28	30	15 830	1 749	**17 841**
Other	386	1 276	361	0	0	250	203	2 941	10 508	509	**16 435**
TOTAL	**167 011**	**362 022**	**27 391**	**1 942**	**14 182**	**28 049**	**1 973**	**40 630**	**138 788**	**15 220**	**797 207**

Source: author's analysis on survey data and national sales data

Removing supplementary systems from the initial dataset results in strong penetration of gas condensing boilers in existing buildings. This is also the case for heat pumps (all types taken together) and biomass. Non-condensing gas boilers – still the most installed technology – as well as gasoil and LPG are severely hit by penetration of efficient and RES-based technologies.

Most air-to-air heat pumps and biomass-fuelled stoves deliver a supplementary service to Italian households. However, the share of such systems used to meet the majority of a dwelling's heating needs is not negligible (e.g. 38% for biomass stoves in 2013).

In the independent segment, biomass has become the main competitor to fossil fuels, if one focuses on annual flows of installed and replaced systems. As shown in Table 3, this result not only applies to gasoil and LPG, but it holds true for natural gas too, once the flows are cut off that refer to installation in areas without a gas grid. Biomass stoves and – to a lesser extent – air-to-air heat pumps are natural gas' main competing technologies, at least as far as data are observed at national level.

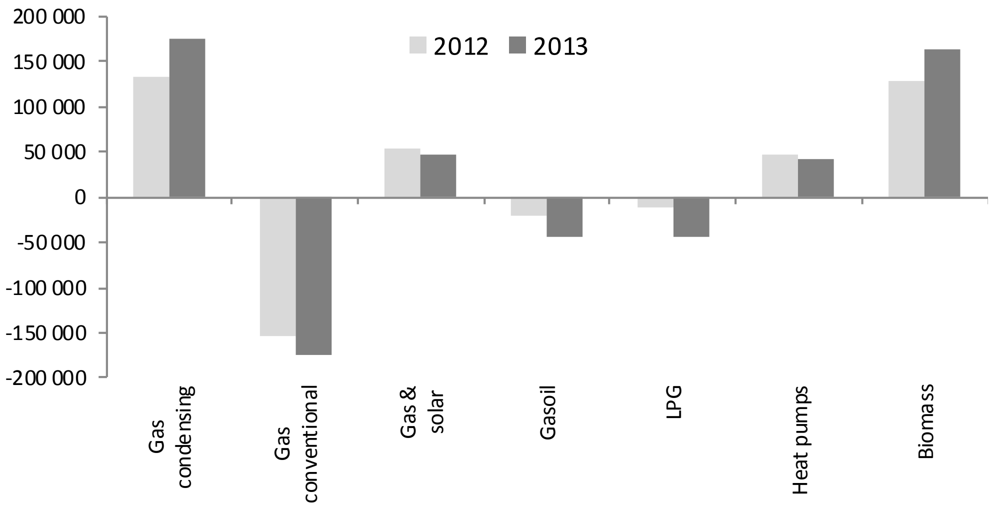
Table 3 – Substitution in the independent segment, main heating systems, with gas network, 2013 (number of systems)

Replaced/supplemented systems	Installed systems: Gas condensing	Gas non-condensing	Gas & Solar	Gasoil	LPG condensing	LPG non-condensing	air-water & water-water HP	air-air HP	Biomass stoves	Biomass boilers	TOTAL
Gas cond.	9 107	8 238	2 536	0	324	0	262	1 035	3 004	555	**25 061**
Gas non-condensing	147 170	345 688	22 297	14	1 771	2 024	1 078	15 716	35 720	3 580	**575 058**
Gasoil	8 007	4 845	1 625	184	29	257	31	484	3 189	471	**19 122**
LPG	2 269	1 691	519	0	779	2 056	32	368	3 991	325	**12 028**
HP	32	216	0	0	0	0	86	9 122	0	0	**9 455**
Biomass	41	69	52	0	0	0	8	0	7 607	767	**8 544**
Other	386	1 276	361	0	0	143	139	2 241	9 008	396	**13 951**
TOTAL	**167 011**	**362 022**	**27 391**	**198**	**2 903**	**4 480**	**1 634**	**28 966**	**62 519**	**6 095**	**663 219**

Source: author's analysis on survey data and national sales data

The net balance between installed and replaced heating and cooling equipment in 2012 and 2013 is shown in Figure 5, with reference to main heating systems only, and including estimated flows in both new and existing buildings. No significant change occurs to the stock of natural gas-fuelled systems, but this is the result of strong penetration of gas condensing boilers and combined gas and solar systems that offset the decrease in the stock of conventional boilers. Differently, a negative balance is estimated for both gasoil and LPG, the former being the result of an even split between areas with and without a gas network, the latter occurring almost exclusively in areas without access to natural gas. The increase in biomass appliances is impressive, and mostly concerns pellet. Finally the main contributor to the increase in the stock of heat pumps is the air-to-air technology (split systems).

Figure 5 – Net penetration balances for the independent segment, main heating systems, 2012-2013 (number of systems)



Source: author's analysis on survey data and national sales data

4.3.2 - Collective segment

Table 4 shows national flows in the collective segment (existing buildings), regardless of the presence of a natural gas grid. In this case, heating systems are centralised by definition, and such systems are assumed to be the main heating source for dwellings, with the exception of solar thermal.

Table 4 – Substitution in the collective segment, all heating systems, 2013 (number of systems)

Replaced/supplemented systems	Installed systems									
	Gas condensing	**Gas non-condensing**	**Gas & Solar**	**Gasoil**	**LPG condensing**	**LPG non-condensing**	**air-water & water-water HP**	**Biomass boilers**	**Solar thermal**	**TOTAL**
Gas cond.	211	0	0	0	0	0	0	0	27	**238**
Gas non-condensing	4 311	1 326	392	0	18	0	1 738	413	136	**8 334**
Gasoil	622	590	118	3 359	62	0	450	499	23	**5 722**
LPG	31	0	10	127	277	221	35	385	6	**1 093**
HP	14	0	0	0	0	0	278	0	21	**314**
Biomass	14	0	0	0	0	0	0	0	22	**36**
Other	53	65	15	0	41	0	149	57	0	**380**
TOTAL	**5 255**	**1 982**	**535**	**3 486**	**398**	**221**	**2 650**	**1 355**	**235**	**16 117**

Source: author's analysis on survey data and national sales data

The gas condensing boiler is both the most installed technology in the collective segment and the one featuring the highest penetration rate. Gasoil is the second most installed technology, but the balance between installation and substitution is negative. When flows are cut-off concerning off-grid areas – as in Table 5 – it becomes clear that heat pumps represent natural gas' main competitor; these are in most cases installed to replace gas-fuelled systems, while only about 10% of newly installed systems replace pre-existing heat pumps.

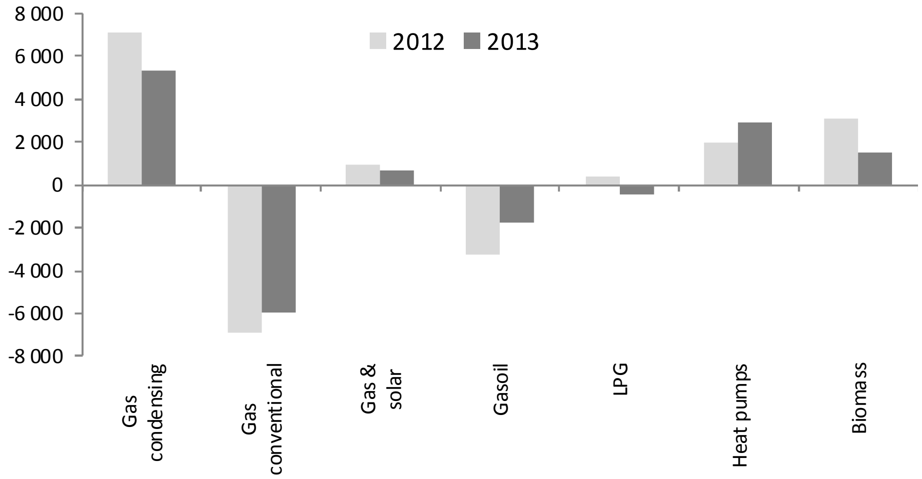
Table 5 – Substitution in the collective segment, all heating systems, with gas network, 2013 (number of systems)

Replaced/supplemented systems	Installed systems									
	Gas condensing	**Gas non-condensing**	**Gas & Solar**	**Gasoil**	**LPG condensing**	**LPG non-condensing**	**air-water & water-water HP**	**Biomass boilers**	**Solar thermal**	**TOTAL**
Gas cond.	211	0	0	0	0	0	0	0	27	**238**
Gas non-condensing	4 311	1 326	392	0	18	0	1 738	413	136	**8 334**
Gasoil	622	590	118	836	0	0	293	363	0	**2 822**
LPG	31	0	10	0	0	0	0	0	0	**41**
HP	14	0	0	0	0	0	255	0	21	**291**
Biomass	14	0	0	0	0	0	0	0	0	**14**
Other	53	65	15	0	41	0	43	0	0	**216**
TOTAL	**5 255**	**1 982**	**535**	**836**	**59**	**0**	**2 329**	**776**	**184**	**11 956**

Source: author's analysis on survey data and national sales data

Once again, net balances show that penetration of gas condensing boilers and combined gas and solar systems – both in new and existing buildings – offsets the considerable amount of conventional boilers being replaced in existing dwellings (Figure 6). The balance is positive for air-to-water and water-to-water heat pumps, although absolute amounts are far below those observed for gas condensing boilers. Penetration of biomass systems takes place in both areas with a gas network and in areas without it.

Figure 6 – Net penetration balances for the collective segment, 2012-2013 (number of systems)



Source: author's analysis on survey data and national sales data

Aside from the survey, data on newly installed district heating substations show high penetration [29]: limited to specific areas of the country – mostly the North – district heating subtracts consistent market shares to gas and gasoil boilers.

5 - Estimating the impact on the energy mix

The results of the survey suggest that in recent years the technology mix for heating and cooling in the residential sector has been heavily affected by fast-growing efficient technologies and RES-based technologies. In order to assess to what extent the energy mix has also been affected, some preliminary elaborations were performed by taking as a focus the consumption of natural gas, i.e. the main energy source for Italian households. In particular, a first attempt was carried out to investigate the combination of the following effects.

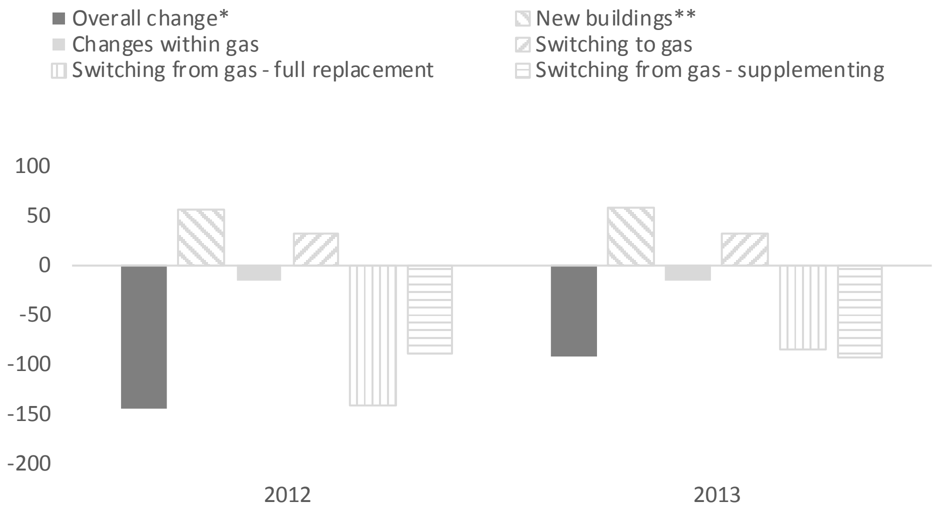
- Installation of gas-fuelled systems in new buildings
- Switching and improved energy efficiency within the natural gas-fuelled group of technologies
- Fuel switching in favour of natural gas-fuelled systems
- Fuel switching from natural gas to energy sources other than natural gas, including both the cases of full replacement and those of partial replacement through supplementary systems.

Inputs to this bottom-up exercise were survey2012 and survey2013 results, including installation and replacement flows grouped per climatic zone, evidence of simultaneous installation of heating generators and radiant heat distribution systems, and efficiency of the replaced boilers. In addition to these inputs, administrative data were used on the stock of dwellings by climatic area and the respective characteristics (size, type of heating system), and literature data were gathered on typical heating needs and typical generation and distribution efficiency[19].

The technology-mix-led total change in natural gas consumption and its determinants are shown in Figure 7. All impacts appear as moderate if compared with household demand for natural gas, the former being never higher than 0.15 billion cubic metres (bcm), the latter varying around 19.5 and 20 bcm in 2012-2013 [30] [31].

[19] Further to what is outlined above, this analysis took into account the space heating use only, limited to heating generation and distribution within the dwelling. District heating was not taken into consideration at this stage.

Figure 7 - Changes in natural gas consumption driven by changes in the technology mix, 2012-2013 (Mcm)



*excluding district heating

**including systems installed in dwellings where no pre-existing plant was in place

Source: author’s analysis on survey data, administrative data and literature data

However, the analysis of individual components to the overall change is useful for interpreting past and future trends as well as to possibly plan corrective measures to current policies.

Technology-mix-led change in natural gas consumption has a downward direction in both 2012 and 2013, its main drivers being full and partial replacement of gas-fuelled systems, which was almost completely attributable to RES-based systems, especially biomass systems.

Another driver having a downward impact on consumption is within-gas technology changes. Indeed these changes brought about little savings in 2012 and 2013. The potential benefits of switching from conventional to condensing boilers were achieved only to a very limited extent, since changes in generation equipment were seldom accompanied by switching to efficient heat distribution systems [27]. Furthermore, the mere replacement of conventional boilers brought about little savings, despite the considerable volume of replaced systems.

Impacts in the opposite direction are those concerning the installation of gas-fuelled systems in new buildings and the switching in favour of gas in existing buildings. As to new buildings, the results of the installer survey suggest that natural gas continues to represent the main energy source for heating. Moreover, in this segment supplementation by RES-based systems is still limited to water heating, which falls beyond the scope of this exercise. The result is an upward change in gas consumption, which is not negligible if compared with the other impacts, yet it has very little significance on the overall gas demand of households. As to existing buildings, switching in favour of natural gas-fuelled systems had very little (upward) impact on consumption, which would have been even lower if efficient distribution systems were combined with the newly installed efficient generators.

Natural gas demand featured little variation from 2011 to 2012 and from 2012 to 2013, which is comparable in magnitude with the changes attributable to the technology mix. However, this consideration is far from leading to the conclusion that the technology mix explains demand changes to a broad extent. Other drivers should be taken into account in further research such as climate, energy efficient investments other than those considered in this analysis – e.g. insulation of buildings and the installation of smart energy controls – and socio-economic drivers that may lead to changes in the end user’s behaviour.

6 - Conclusions and future research directions

Surveying installers allowed to cover an acceptable share of the residential heating and cooling market in Italy (almost 1.5%), and further allowed to observe competition and combination among technologies, through segmentation of the market.

Results show significant differences between the independent and collective segments.

As to the independent segment, both administrative data on sales and data gathered on installation works carried out by the respondents in 2012 and 2013 suggest that competition is fierce between fossil-fuelled technologies – in particular natural gas – and technologies that use RES. Not only this is apparent in new buildings, but it also holds true in existing buildings.

Among the first group of technologies, penetration rates are high for condensing boilers – especially those fuelled by natural gas – but the market shares of conventional systems remain higher.

Among technologies that use RES, penetration of biomass-fuelled systems is impressive: new flows of installed systems concern mainly stoves and fireplace stoves, i.e. heating equipment that in most cases serves as a supplementary system to the dwelling's main heating system – exceptions being non negligible in number. Diffusion of heat pumps is led by air-to-air systems. Similar to biomass stoves, these are in most cases used as supplementary systems – or even for cooling only – but use as the main heating system concerns a non-negligible number of cases.

As to the collective segment, the distance is greater between fossil-fuelled technologies and renewable ones. Air-to-water and water-to-water heat pumps have emerged as the main competitor to natural gas, in areas with the gas network. The diffusion of biomass-fuelled systems is lower than for independent systems, and takes place to a large extent in areas where natural gas cannot be accessed.

Data on the inflows and outflows of heating and cooling equipment may serve the purpose of estimating and modeling changes in energy consumption and in the energy mix for heating and cooling, as well as to validate or integrate administrative data or other survey data.

With a focus on natural gas consumption, a first attempt was carried out to estimate how changes in the technology mix have affected the energy mix. Results suggest that estimated (downward) impacts account for a very little share of the overall demand for gas by households. Among the causes of this outcome are the fact that most RES-based systems do not fully replace gas-fuelled systems, and the fact that efficient heat generation technologies are not installed in combination with efficient heat distribution technologies. Moreover, RES obligations in new buildings have not brought about significant effects yet.

So far, then, policies have been implemented slowly and their effectiveness is questionable. Also, the cost-effectiveness of financial support policies should be considered in the light of the results of this – and similar – analyses, and the design (requirements) of support schemes adjusted when necessary: incentives are often granted to generation equipment, regardless how such pieces of equipment are used within the whole heating system of a building or dwelling.

Returning to the role of natural gas for heating in the household sector, it may be expected that more extensive energy efficient investments in buildings, together with tighter regulation, will bring about increased downward pressure on natural gas consumption in the years to come. For these reasons, monitoring the technology mix remains a useful exercise. Better monitoring will encompass energy efficiency at all stages and for a greater spectrum of uses, including improvements in the energy performance of buildings, heat and sanitary hot water generation and distribution, cooling, and energy control and metering equipment.

Finally, analyses of the impact of the technology mix on energy consumption should be conducted – to the possible extent – in combination with the analysis of the other drivers of consumption, *in primis* climate, wealth, and relevant social-behavioural changes.

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Residential Solar Water Heating - Measurement and Verification Case Studies

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ABSTRACT

South Africa is currently experiencing an electricity crisis. This, combined with the high levels of solar irradiation as well as the power utility's need to reduce the country's peak demand through DSM (Demand Side Management), has promoted the installation of solar water heaters (SWHs) in homes across the country. This paper presents three case studies which were M&V'd according to the IPMVP (International Performance Measurement & Verification Protocol). The methodology used does not require baseline measurements since the baseline is calculated from continuous measurements of thermal energy delivered by the newly installed SWHs and estimation of standing losses of the replaced electric water heater (EWH). This allows the homeowner to go ahead with the installation of the SWH without waiting for M&V to establish a baseline for the EWH which is being replaced. This method is preferred by homeowners and the DSM utility alike, since the installation of the SWH is not delayed by M&V. A measurement system including an electric power meter, inlet and outlet water temperature probes, ambient temperature probe, flow meter and GSM modem were developed to measure the service level and performance of the SWH. This measurement system along with a method for modelling the usage of an EWH are crucial to the M&V methodology employed. This paper describes the type of systems investigated, the M&V metering, M&V methodology, and the payback period of each system. The sensitivity of the savings with respect to EWH standing losses is investigated. This case study provides valuable information for those interested in studying or performing M&V on SWHs.

Introduction

South Africa has an electricity supply shortage, however the northern regions of the country, based on the escarpment, experience high levels of solar irradiation [1]. This has prompted the installation of SWHs across the country [2] .

This paper focuses on determining the savings that can be achieved by SWHs in the residential sector. Three case studies were investigated. The IPMVP [3] was used to develop a methodology for determining the savings from these systems. This methodology involves the use of a custom built measurement system to record the SWH usage and performance data.

The three systems investigated were, a 100 litre system, used by a bachelor, a 150 litre system, used by a household of six and a 200 litre system, used by a household of four. All three systems have a backup electrical heating element rated at 2.5 kW.

The purpose of this case study is to determine the energy savings, conduct a payback versus EWH standing loss and payback versus capital investment analysis. The Monte Carlo method was used to vary EWH standing losses so that one may view the effect that different EWH standing losses have on the SWH payback period.

Typically, savings of such systems are determined by comparing electricity bills of the pre-retrofitted and the post-retrofitted systems. However that approach is flawed in that it does not account for potential changes in hot water usage after the installation of the SWH. Furthermore, it does not account for the possibility of other changes in household consumption occurring between the baseline and assessment periods.

In this analysis, the approach taken involves the isolation of the energy consumption of the hot water system from that of the rest of the house and the reporting of savings relative to the hot water usage levels demanded of the SWHs.

SWH system specifications

The system specifications of the three SWHs being investigated are displayed in Table 1 below.

Table 1. System Specifications

System	**100 Litre**	**150 Litre**	**200 Litre**
Working Pressure	0kPa	0kPa	0kPa
Type of Collectors	Evacuated Tube	Evacuated Tube	Evacuated Tube
Number of Tubes	15	20	26
Collector Aperture Area	1.3 m^2	1.7 m^2	2.2 m^2
No. Occupants	1	6	2-4
Set point temperature	55 ^{0}C	65 ^{0}C	65 ^{0}C

The basic low pressure SWH system consists of an inner tank, insulation, outer tank, heat collectors and a support base. The investigated low pressure SWHs include additional equipment such as an intelligent heating controller, heating element, storage tank water temperature sensor and outlet water

pressure boosting pump [4]. Figure 1 presents a photo of the 100l SWH installation.

Figure 1. 100l Solar Water Heater Installation

Metering System

The metering system, shown in Figure 2, was developed by a company specializing in measurement equipment. The meter system is powered by a 12 volt rechargeable battery and two 10W photovoltaic panels. Data is obtained by downloading it remotely using a GSM modem.

The metering system installed on the SWHs captures the following data: inlet cold water temperature (^{0}C), outlet hot water temperature (^{0}C), element usage (kWh), ambient Temperature (^{0}C), solar irradiance (W/m^2) and flow (L). The data is captured by the meter on a minutely basis.

Figure 2. SWH measurement system

Savings Calculation Methodology

Retrofitting an EWH with a SWH should reduce the daily electrical power demand and save energy. The determination of the energy savings from the retrofit will be done using a Measurement and Verification (M&V) methodology [3]. The M&V methodology used, is in accordance with the IPMVP [3] and SANS 50010 [5].

The IPMVP [3] gives the following basic equation for determining the avoided cost energy savings:

$$S = Adjusted\ Baseline - \ Actual \qquad (1)$$

The Baseline being the consumption of the EWH and the Actual being the electricity consumption of the SWH. The Adjusted Baseline is the energy that the EWH would have consumed had it been operating in the conditions of the SWH. Thus the adjusted baseline represents the energy consumption of the EWH supplying the same amount of hot water as is required of the SWH.

The general energy savings equation stated in the IPMVP has been adapted to suit these SWHs. The energy saving for the system is given by the following equation.

$$S = BL_{Adj} - (E_{element} + E_{pump}) \quad (2)$$

Where S is the energy savings

BL_{Adj} is the adjusted baseline energy

$E_{element}$ and E_{pump} are the electric energy used by the backup heating element and outlet water pump of the SWH

This gives the avoided cost savings where the savings are reported relative to the way in which the SWH is used. Whether the change from an EWH to a SWH itself causes the household occupants to change their habits and hot water usage was not determined – since only post-retrofit water usage is measured.

There are 3 possible cases regarding a change in hot water usage pre- and post- retrofit:

- Hot water usage goes up after SWH installation (e.g. due to residents thinking that they are saving energy and can use more hot water)
- Hot water usage stays the same
- Hot water usage decreases (e.g. due to increased awareness of energy issues and willingness to save extra money)

For case 1 and case 3 it is assumed that the change would have occurred anyway in this analysis.

The calibrated simulation option under the IPMVP was chosen where the pre-retrofit system usage (baseline) is simulated [3], [6]. The adjusted baseline is calculated using the following equation:

$$BL_{Adj} = Q_{actual} + SL \quad (3)$$

Where BL_{Adj} is the adjusted baseline energy

$\mathrm{Q_{actual}}$ is the thermal energy used by the occupants in the form of hot water from the SWH and

SL is the standing losses of the EWH

Therefore the baseline is calculated relative to the hot water usage levels associated with the SWH.

The actual energy $\mathrm{Q_{actual}}$ is determined from the following equation:

$$\mathrm{Q_{actual}} = m_{actual} \cdot c_p \cdot (T_{out\,(actual)} - T_{in\,(actual)}) \quad (4)$$

Where $\mathrm{m_{actual}}$ is the mass of the hot water withdrawn from the SWH by the occupants

$c_p = 4180$ J/K is the heat capacity of water

$T_{out\,(actual)}$ is outlet temperature of the hot water from the SWH

$T_{in\,(actual)}$ is inlet temperature of the cold water entering the SWH

The metering system installed on the SWH system captures the above data from the SWH system.

The novelty of this methodology is that it does not require baseline measurements since the baseline is calculated from continuous measurements of thermal energy delivered by the newly installed SWH and estimation of standing losses of the replaced EWH. This allows the homeowner to go ahead with the installation of the SWH without waiting for M&V to establish a baseline for the electric water heater which is being replaced. This method is preferred by homeowners and the DSM utility alike, since the installation of the SWH is not delayed by M&V.

Standing Losses

In South Africa standing losses are regulated by the SABS standard SANS 151 [5] which requires standing losses to be less than a certain amount of kWh per day under certain conditions. Table 2 shows the SABS maximum permissible standing losses for different size EWHs.

Table 2. SANS 151 standing losses (kWh/day) for different capacity EWHs

Capacity (l)	Standing Loss (kWh/day)
100l	2.2 kWh/day
150l	2.6 kWh/day
200l	3.0 kWh/day

Based on a recent studies on standing losses of South African EWHs [7], [8], the standing losses can vary depending on the EWH installation (vertical vs horizontal) and the presence of extra thermal insulation on the EWH and hot water pipes. According to equations (2) and (3), the higher the standing losses, the higher the baseline and potential for savings.

It is possible to determine a heat loss coefficient from the maximum permissible standing losses and then determine the standing losses dynamically based on the temperature difference between the EWH tank water and the ambient environment. However, the overall daily results do not change significantly using this method as compared to using a constant value for the daily standing loss.

Data Analysis

Tables 3-4 and Figures 3-6 present the results of the savings analysis.

The 100 litre's total flow and water usage are the lowest of the three, yet savings produced are on par with the other two households. This is because this SWH's backup element is set to only turn on if needed between the times of 4pm-5pm. Upon monitoring the system, it was observed that the auxiliary electrical element only operated in the winter months for approximately 13 minutes per day thus contributing to the energy saved.

The 100 litre system's set point is the lowest of the three systems (55℃). This system is also the most efficient because out of the three systems it used the auxiliary element the least. The 150 and 200 litre systems' set point were 65℃. The higher set point results in higher electricity usage.

The 150 litre system's total flow is the highest, this is expected as it is used by a family of 6. Correspondingly, this system has the highest energy savings. This household's hot water usage averages 65 litres per person per day.

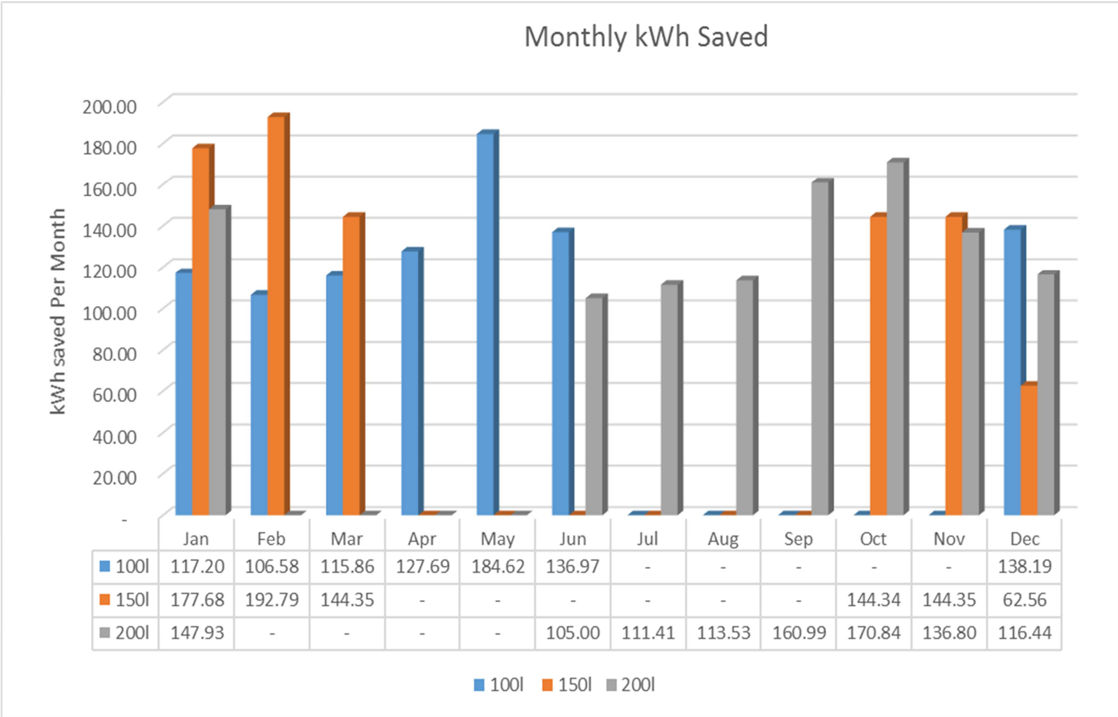
The 200 litre system has a lower than expected water usage and energy savings. This is probably due to the household occupancy being two, during weekdays, and four, during weekends. It is interesting to note the large role occupancy, SWH settings and water usage play in energy saved.

	Ambient Temp (^{0}C)	hot water usage (l)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Average Q (kWh)	Baseline (kWh)	Element Use (kWh)	Savings (kWh)
100l SWH	18.07	55.5	19.7	52.4	2.06	4.46	0.16	4.29
150l SWH	23.99	393.90	23.69	49.41	11.76	14.36	9.56	4.80
200l SWH	-	101.61	16.5	54.8	4.49	7.49	2.84	4.65

Table 3. Average Daily SWH usage statistics

	Ambient Temp (^{0}C)	hot water usage (l)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Average Q (kWh)	Baseline (kWh)	Element Use (kWh)	Savings (kWh)
100l SWH	18.27	1 665	19.7	52.4	61.71	133.71	4.88	128.82
150l SWH	23.99	11 816	22.90	49.41	352.91	430.91	286.83	144.08
200l SWH	-	3 048	16.5	54.8	135.7	207.7	85.21	132.9

Table 4. Average Monthly SWH usage statistics



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
100l	117.20	106.58	115.86	127.69	184.62	136.97	-	-	-	-	-	138.19
150l	177.68	192.79	144.35	-	-	-	-	-	-	144.34	144.35	62.56
200l	147.93	-	-	-	-	105.00	111.41	113.53	160.99	170.84	136.80	116.44

Figure 3. Monthly Saving Comparison of the SWH's

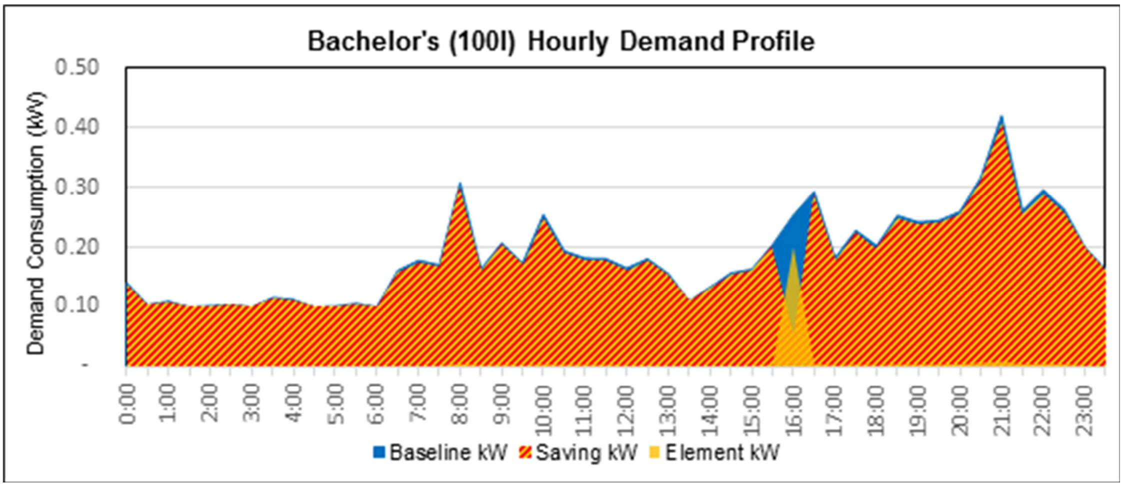
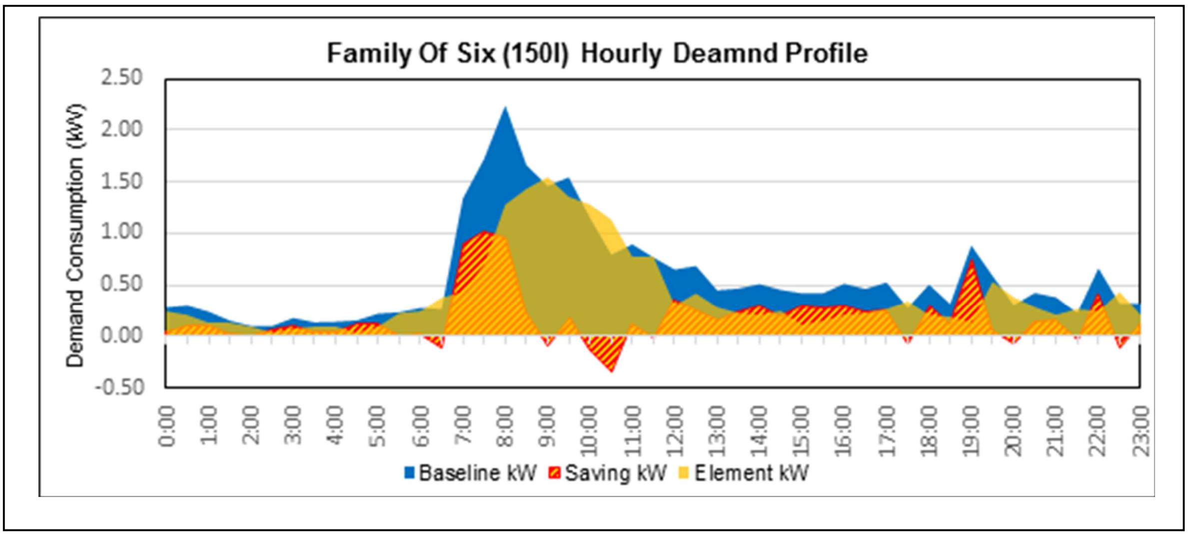


Figure 4. Bachelor's (100l) hourly demand profile



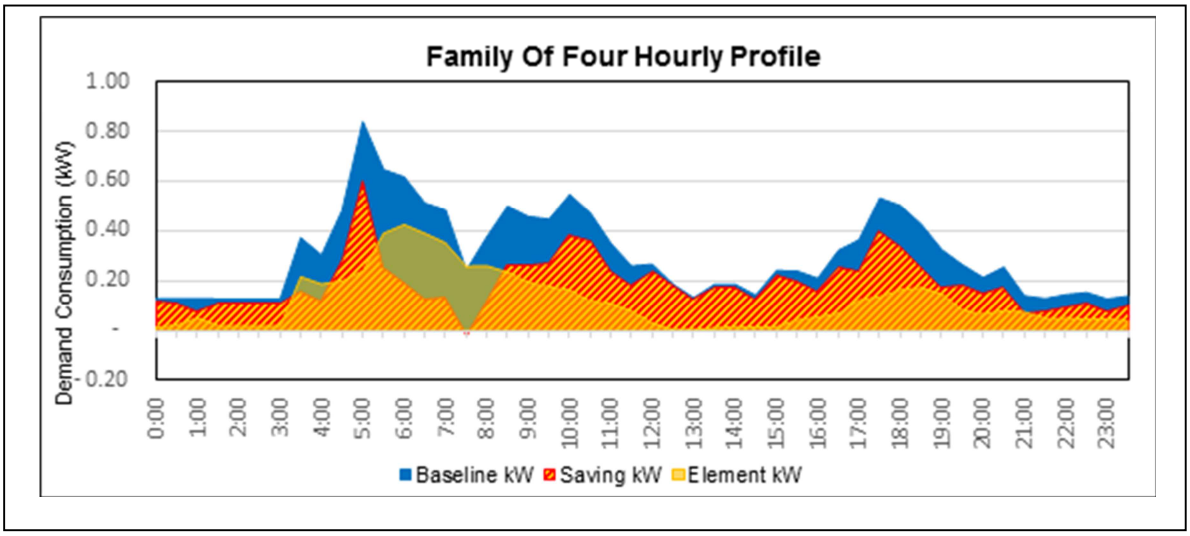


Figure 5. Family of six (150l), hourly demand profile

Figure 6. Family of four (200l), hourly demand profile

From the bachelor’s demand profile represented in Figure 4, one can observe that water usage occurs mostly in the late afternoon to evenings and since the element is not required to regularly maintain water temperature one can see that there the savings are almost equal to the baseline.

Looking at Figure 5 and Figure 6 one can see that the auxiliary element is required to maintain water temperature on a more regular basis especially during the morning periods due to the lack of solar thermal energy from dusk till dawn. What can be discerned in all three cases, is that the retrofitting of the SWH has played a significant part in reducing the power demand during the residential peak periods (7am-10am and 6pm-9pm).

Payback Calculations

The payback calculation of each system is based on the discounted cash flow calculation method [9].This method is not the most accurate method in determining a payback of a system but it would give a general estimate of each systems payback period [10]. The comparison was carried out over a 10 year period. This comparison was of interest as it could validate the profitability of the installation and use of a SWH. A period of 10 years was chosen since that is the estimated life span of a SWH.

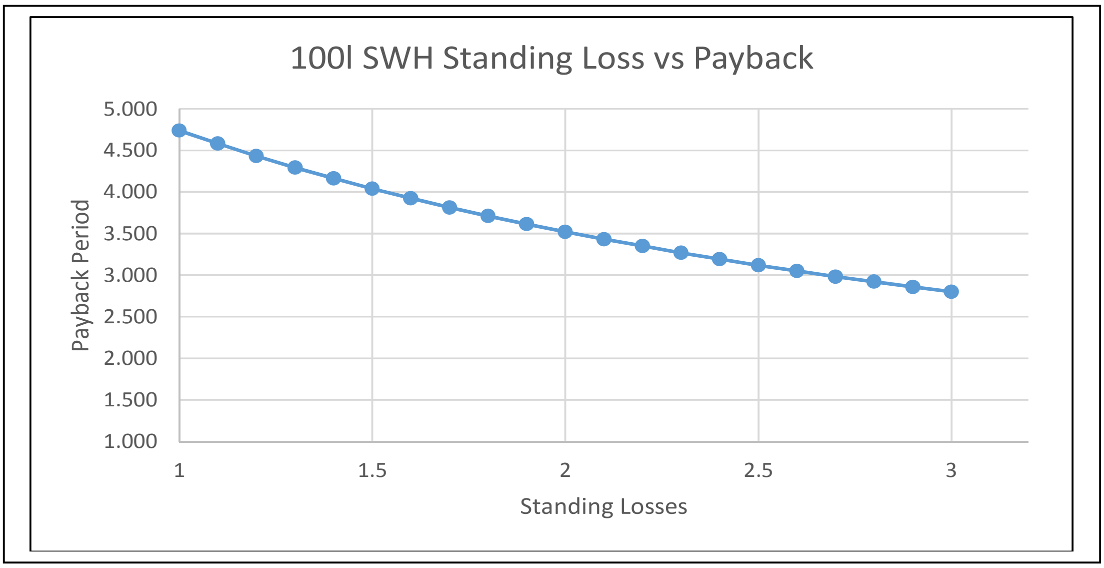
Table 6 presents the data used in the payback analysis. The pages that follow show the standing loss versus payback graphs (Figures 7-8) that are derived from the method above while varying the standing losses. South Africa has a flat rate electricity tariff throughout the day for residential consumers. The 2015 tariff is ZAR 1.20 per kWh (USD 1 = ZAR 12).

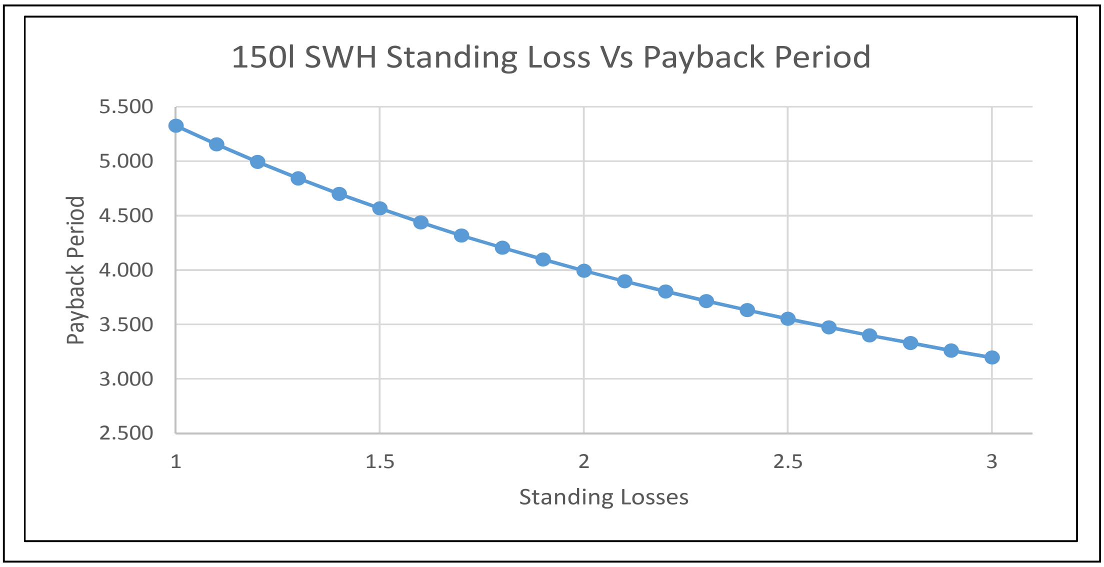
Table 5. Annual savings and payback based on the maximum permissible standing loss

	Standing Loss (kW/day)	Average Annual Savings (kWh)	Estimated Payback Period (Years)
Bachelor, 100 litre System	2.4	1 566	3.2
Family Of 6, 150 litre System	2.6	1752	3.3
Family Of 4, 200 litre System	3	1 624	4.1

Table 6. Discounted cash flow factors

Capital cost (investment interest rate)	6%
Electricity inflation	12%
Electricity cost (year 1)	R1.20/kWh
Consumer price index	6%





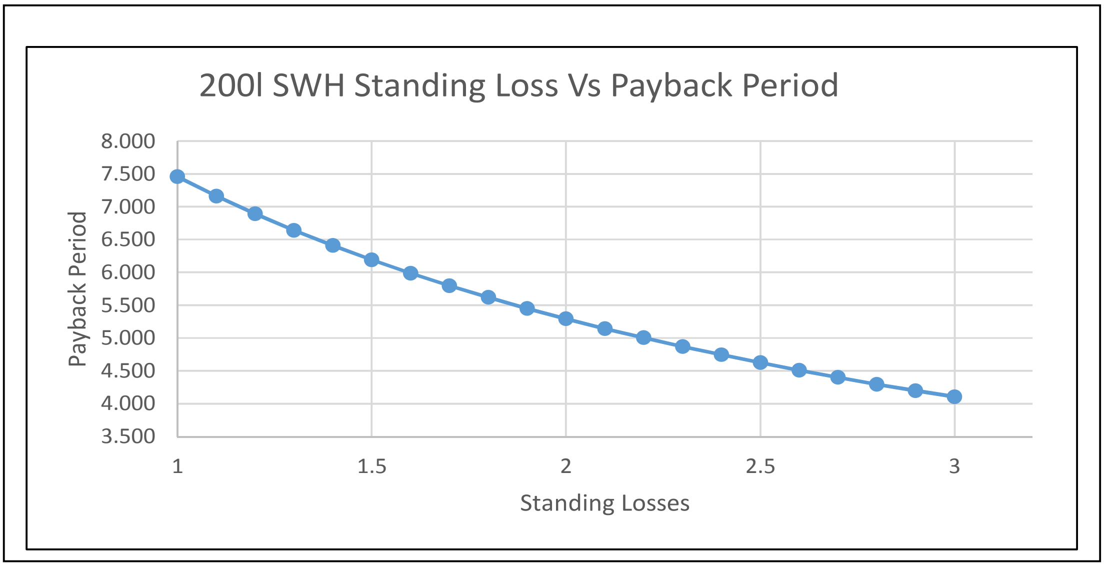
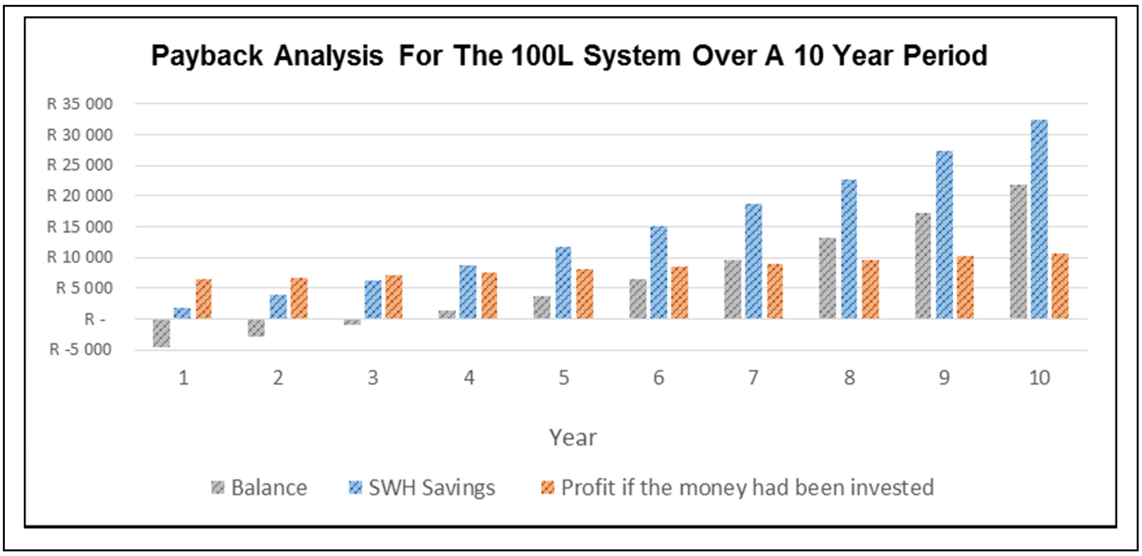
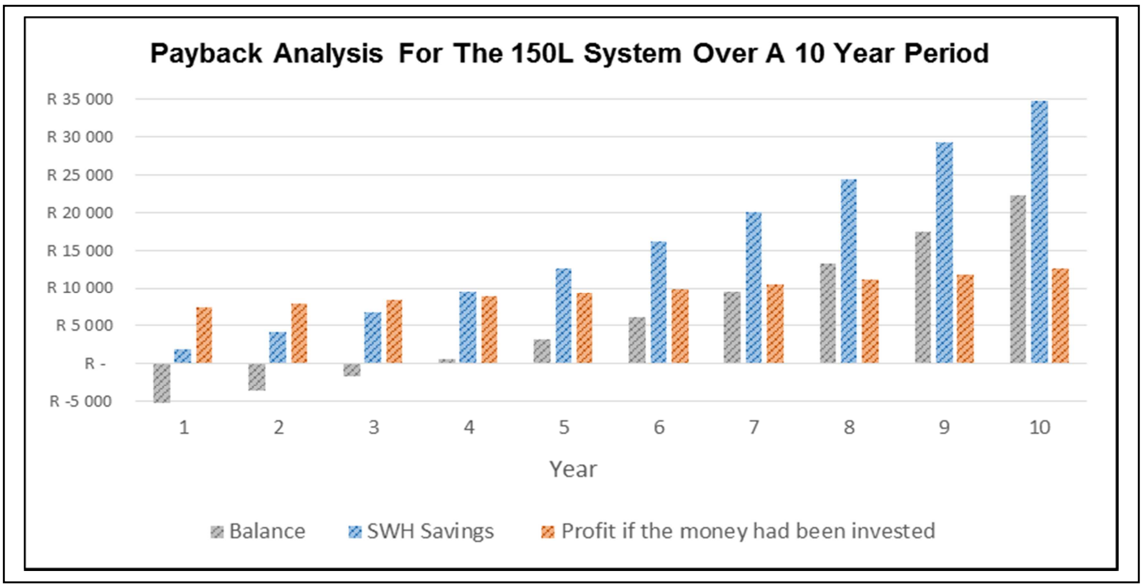


Figure 7. Standing Loss versus Payback Period for each System





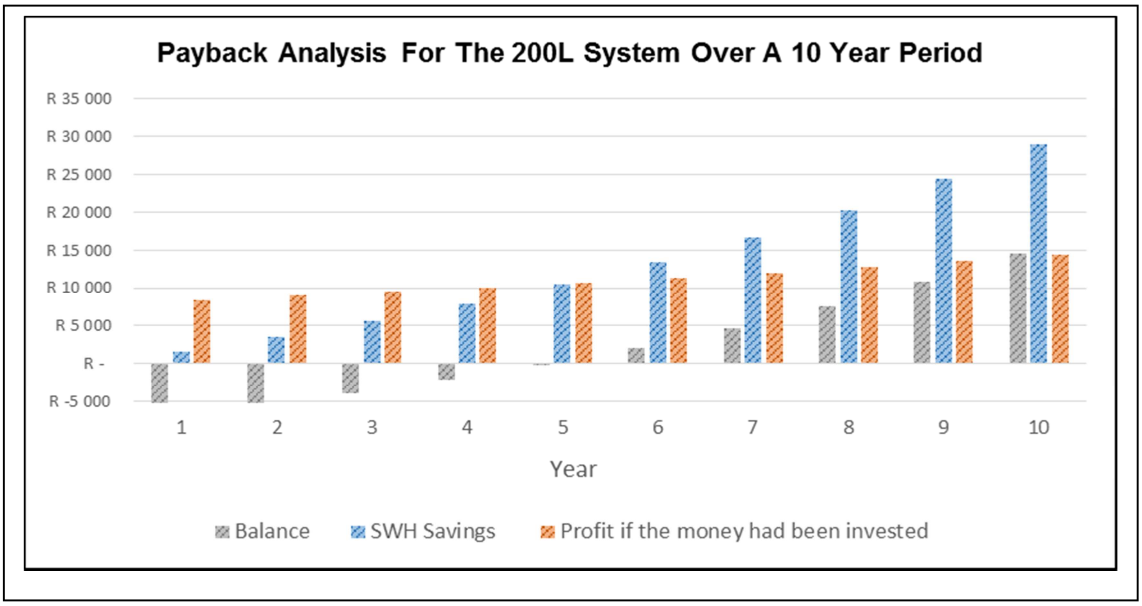


Figure 8. Payback versus Capital Cost Investment

Observing the capital cost and standing loss versus payback graph in Figures 7-8 one can observe that the estimated payback period for a SWH system would be between 4-6 years. This is a respectable payback period as one breaks even at the half way stage of the SWH's life span. It was interesting to observe that after factoring in electricity inflation, CPI and investment interest rate, one would still save more money through the installation and use of a SWH than by investing the capital in a bank account.

Observing the effect of standing losses on the payback period one can see that as the standing losses increases the payback period deceases. The standing losses are those of the EWH system i.e. the pre-retrofitted system. Therefore the more inefficient the EWH, the bigger the savings would be after the EWH is upgraded to a SWH.

Conclusion

In this case study three SWHs in different homes and operating conditions were investigated. From the analysis of the data it is clear that all three systems produced energy savings as well as demand reduction during peak usage periods, irrespective of the variable water usage contributed by the households.

The payback analysis produced an interesting study and highlights the important role standing losses play in the energy savings and payback period of a SWH. A major benefit of the SWH is that one would eventually save more money with a SWH than simply investing the money in a low risk fixed deposit account.

The novel methodology implemented in this study showed evidence that the retrofitted SWH system produced savings with respect to an EWH. While SWHs are significantly more expensive than EWHs they require less energy from the grid. This benefit makes the SWH an attractive choice over an EWH. Although this benefit makes a SWH a practical option, one should place emphasis on the user consumption, sizing and pricing of a SWH system in order to achieve the best payback.

The knowledge and experience gained from investigating these SWH's will be used in the design as well as the implementation of a Measurement and Verification SWH methodology for a nationwide SWH M&V rebate programme in South Africa.

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Heat Pump Water Heaters: Controlled Field Research of Impact on Space Conditioning and Demand Response Characteristics

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Abstract

A new generation of heat pump water heaters (HPWH) has been introduced into the U.S. market that promises to provide significant energy savings for water heating. Many electric utilities are promoting their widespread adoption as a key technology for meeting energy conservation goals and reducing greenhouse gas emissions. There is, however, considerable uncertainty regarding the space conditioning impact of an HPWH installed in a conditioned space. There is also uncertainty regarding the potential for deployment of HPWHs in demand response (DR) programs to help manage and balance peak utility loads in a similar manner as conventional electric resistance water heaters (ERWH).

To help answer these uncertainties, controlled experiments have been undertaken over 30 months in a matched pair of unoccupied Lab Homes located on the campus of the Pacific Northwest National Laboratory (PNNL) in Richland, Washington. The water heater closet in the Lab Homes is in conditioned space; therefore, taking supply air and injecting cool exhaust air from an HPWH will interact with space conditioning within the homes. Initial experiments were conducted with the second-generation General Electric (GE) "Brillion™" heat pump water heater in several configurations: 1) unducted, 2) exhaust-air ducted, and 3) fully ducted to ascertain the impact of the HPWH on space conditioning. Experiments also were conducted under simulated occupancy conditions on the GE units to determine the DR of the units under multiple scenarios.

Subsequent DR experiments were conducted in the Lab Homes with Sanden carbon-dioxide (CO_2) refrigerant HPWHs as part of a project conducted by Washington State University Energy Program with funding from Bonneville Power Administration. These HPWHs are new to the U.S. market but not yet commercially available. Two units were evaluated: 1) a split system with an outdoor compressor and an 80-gal (303 L) indoor water tank and 2) a 40-gal (151 L) unitary unit installed in the Lab Home water heater closet and fully ducted (supply and exhaust air).

1.0 Introduction

In the United States, water heating represents the second largest household energy expense behind space heating, representing approximately 18% of residential energy consumption, or approximately 1.8 Quads annually [1]. Efficient water heater options are necessary to achieve significant energy savings in the residential sector and therefore the U.S. Department of Energy (DOE) recently completed new energy conservation standards for natural gas, oil, and ERWHs between 20 and 80 gal (76 and 303 L) [2]. For storage water heaters with volumes of 55 gal (208 L) and below (representing the majority of new water heaters for dwellings) the new standards will increase the efficiency by approximately 4% [2].

For water heaters larger than 55 gal (208 L), a much bigger jump in efficiency is mandated. The new standards for these larger water heaters can be met using electric heat pump (HPWH) and gas condensing technology. HPWHs save at least 50% and condensing gas units about 25% compared to today's conventional tank-type ERWHs [3].

Electric HPWHs ranging in size from 40 to 80 gal (151 to 303 L) offer the most efficient option for the 41% of homes equipped with ERWHs, with a theoretical energy savings of up to 63%.[1]

[1] Based on the DOE test procedure [9], and comparison of an ERWH (Energy Factor, EF = 0.90) versus a HPWH (EF = 2.4)

However, significant barriers must be overcome before this technology will reach widespread adoption. One barrier noted by the Northwest Energy Efficiency Alliance (NEEA)[2] is that HPWH products are not ideal for northern climates, especially when installed in conditioned spaces. HPWHs exhaust cool air as they heat the water, and there may be complex and detrimental interactions with the homes' space conditioning system for units installed in a conditioned space [4]. Such complex interactions may decrease the magnitude of whole-house savings available from HPWHs installed in the conditioned space in cold climates and could lead to comfort concerns [4, 5]. Modeling studies indicate that the installation location of HPWHs can significantly impact their performance and the resultant whole-house energy savings [6, 7]. As a result, NEEA's Northern Climate HPWH Specification, which describes the characteristics a HPWH must have to be incentivized in cold climates in the Pacific Northwest, requires exhaust ducting for a Tier II product and full ducting for a Tier III product (see www.neea.org/northernclimatespec).

In addition, if exhaust-air ducting on HPWHs is found to be beneficial in some or all climates, it will be important to understand the source and temperature of supply air (whether it is the home's conditioned air or outside air brought into the home) and the implications for interior depressurization, particularly for tight homes.

Another barrier is the impact of HPWHs on DR programs because DR characteristics currently are unknown for HPWH technology. Many utilities currently employ large storage tank ERWHs to reduce peak load by turning off the water heater during times of peak demand. Some utilities also are demonstrating the potential of using ERWH to increase load for areas with high renewable energy penetration and to provide additional balancing and ancillary services. As HPWHs begin to penetrate the market in the residential sector, utilities will need to better understand the DR capability and characteristics of HPWHs.

2.0 Demand Response

DR benefits to utilities include increased system reliability, defrayed cost of new infrastructure investment, reduced fuel consumption, improved system efficiency, and decreased carbon emissions through increased penetration of intermittent renewable resources. When considering grid stability and reliability, several types of DR are considered:

- *Peak curtailment*, or *peak load reduction*, which drops non-critical loads for a period of 4-6 hours during the time when power use is highest and the strain on the grid is greatest. This can prevent the need to bring on inefficient, fossil fuel-fired "peaking plants" that exist solely to generate electricity during the peak 4-6 hour period and are otherwise turned down or off.

- *Balancing reserves,* or *regulation services*, responds to hourly or sub-hourly changes in generation capacity either because of inherent variability in the generation resource or large disturbances in the grid (e.g., transmission fault). Balancing reserves can be implemented for either a shortage of generation capacity (commonly referred to as INC) or a surplus of generation capacity (commonly referred to as DEC).

- *Ancillary services* that adapts to sub-minute fluctuations in voltage or frequency to maintain consistent electricity service and distribution.

Several studies have previously evaluated the potential of ERWH to provide peak curtailment, balancing reserves, and ancillary services using models and found significant potential and benefit for ERWH to perform these grid functions [8, 10, 11, 12]. However, no extensive field testing has verified these model results. In addition, new HPWH technology has the potential to dramatically decrease the electricity use and peak load of residential water heating. Consequently, use of more efficient heat pump technology may also limit the magnitude of the water heater for DR.

[2] www.neea.org

3.0 HPWH Experiments

Given there is a need to understand both the efficiency and impact of a HPWH installed in a conditioned space in a home and the potential for deploying a HPWH for DR compared to the DR characteristics of ERWHs, a set of experiments were conducted in the PNNL Lab Homes[3] over a 3-year period to better understand the attributes of a HPWHs. Three diverse types of HPWHs were tested: 1) a GE second-generation 50-gal (189 L) GeoSpring Hybrid Water Heater (model GEH50DEEDSR), which is enabled with Brillion™ wireless communication and control technology to test the thermal envelope and HVAC impact and DR characteristics;[4] 2) a Sanden GES-15QTA 40 gal (151 L) integrated heat pump water heater using CO_2[5] as the heat pump refrigerant to test DR; and 3) a Sanden GAU-315EQTA split system heat pump with an 80 gal (303 L) storage tank also using CO_2 as the refrigerant to test DR. The Sanden unitary HPWH was fully ducted during all experiments with this unit per manufacturer's specifications.

3.1 PNNL Lab Homes Testing Platform

The matched pair of PNNL Lab Homes (designated Lab Home A and Lab Home B) provide a unique platform in the Pacific Northwest region for conducting experiments on residential-sector technologies. These unoccupied electrically heated and cooled 1500 square-foot homes are sited adjacent to one another on the PNNL campus in Richland, Washington. The homes are fully instrumented with end-use metering (via a 42-circuit panel), indoor and outdoor environmental sensors, and remote data collection. Figure 1 is a floor plan of the Lab Homes noting the location of the water heater and the required ventilation (transfer) grills installed in interior walls of the home to allow air circulation for the integral HPWHs that were tested.

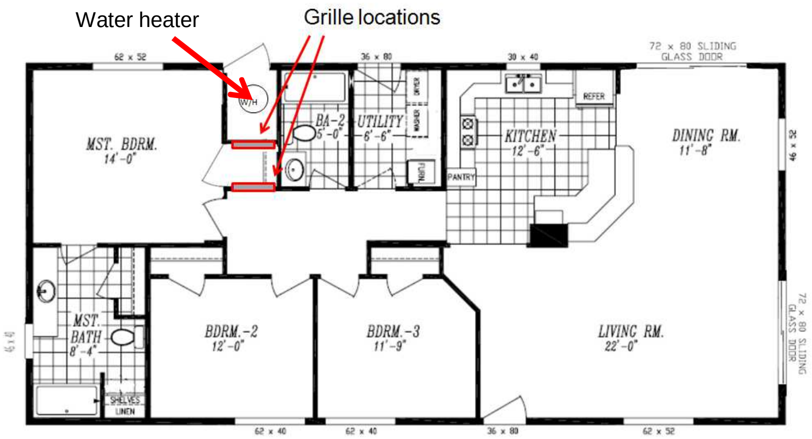

Figure 1. Floor plan of Lab Homes with water heater and transfer grills locations noted.

3.2 Experimental Design

The experiments were designed evaluate the HVAC system (space conditioning) impact and DR characteristics of the GE GeoSpring HPWH, and the DR characteristics of the Sanden integrated CO_2 heat pump water heater and the Sanden CO_2 split-system heat pump water heater. Occupancy and hot water use schedules were simulated to isolate the performance, impact, and DR of the HPWHs from all other variables. Table 1 summarizes the six experiments.

Table 1. Summary Description of HPWH Experiments in the PNNL Lab Homes.

Experiment	Equipment	Experiment Description	Time Period

[3] A full description of the Lab Homes is found at http://labhomes.pnnl.gov.

[4] A full description of the features and controls capability of the GE GeoSpring HPWH is found elsewhere [14].

[5] CO_2 has a very low Global Warming Potential of 1. A full description of the features of both Sanden units tested is found elsewhere [15].

1	GE GeoSpring HPWH	HVAC impact of ducting compared to unducted configuration	June-August
2	GE GeoSpring HPWH	HVAC impact of ducting compared to unducted configuration	Dec-Jan
3	GE GeoSpring HPWH	Water heating energy use of ducted and unducted configurations	June-August Dec-Jan
4	GE GeoSpring HPWH ERWH	DR characteristics of the GeoSpring HPWH in unducted configuration compared to DR of ERWH	April-May
5	Sanden GES-15QTA HPWH Unitary System	DR characteristics	October
6	Sanden GAU-315EQTA HPWH Split System	DR characteristics	October

As a part of thermal impact experiments 1 and 2, the comfort (i.e., room temperature) was determined; however the results are not reported in this paper but are reported elsewhere [14]. In addition, the COP of the Sanden split system under DR stress is currently being evaluated in the laboratory and will be reported in late CY2015. The baseline efficiency in the laboratory was established in research prior to the Lab Homes testing [15].

Figures 2a and 2b show the GE GeoSpring HPWH installed in the Lab Homes for experiments 1-4. Figures 3a and 3b show the Sanden HPWHs installed in the Lab Homes for experiments 5 and 6.

Figure 2a. Installed GE HPWH without ducting in Lab Home B.

Figure 2b. GE HPWH with exhaust and supply ducting in Lab Home A.

The supply air for the fully ducted configuration of the GE GeoSpring units was supplied from the home crawlspace near the center of the home through a 6-in. flexible duct.[6] The exhaust air was drawn by a small fan through 6-in. flexible duct from the unit and exhausted via a standard dryer-type vent installed at the bottom of the closet door. The exhaust duct fan was needed to provide sufficient airflow across the heat pump, as the GE GeoSpring HPWH was not designed for exhaust or full ducting as purchased. The measured airflow through the ducting during these experiments, with the supplemental exhaust fan running, was 166 CFM (282 m^3/hour) for the exhaust-only ducting and 117 CFM (199 m^3/hour) for the full ducting, both of which are in accordance with installation recommendations [4]. For the unducted configuration, the master bedroom closet was closed and any air circulation around the HPWH was provided by four transfer grills (two in the closet wall and two in the hallway wall).

[6] Note that the homes are both completely skirted by ~2 inch insulating vinyl-covered foam panels.

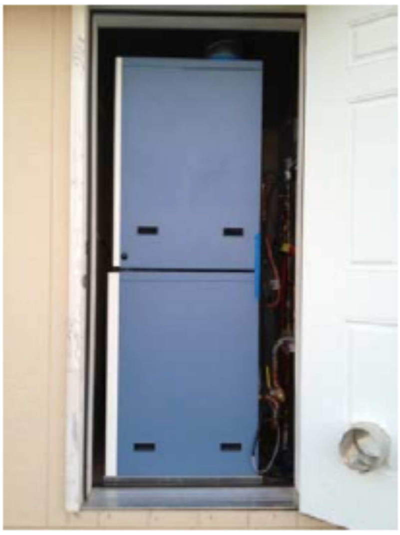

Figure 3a. Sanden unitary unit installed in Lab Home A.

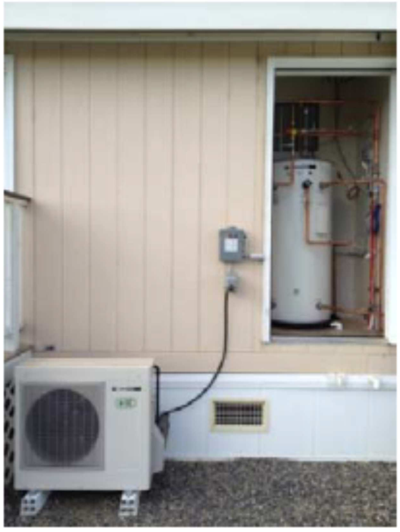

Figure 3b. Sanden split system installed in Lab Home B.

3.3 Data Capture and Experimental Configuration

Following are summary descriptions of the experimental setup for the Lab Homes. These descriptions include how energy (electricity) was measured, how occupancy was simulated, how the HVAC system was operated, and how temperature, humidity, and water flow were measured. A more detailed description can be found elsewhere [14,16].

3.3.1 Electrical Energy

Whole-house electrical power and circuit level (true) power was measured at the 42-circuit breaker panel with current transformers. Data were captured at 1-minute intervals via a Campbell Scientific data logger.

3.3.2 Simulated Occupancy

To simulate occupancy, hot water draw profiles were implemented identically in both homes. The hot water draws used a modulating solenoid valve at the kitchen sink hot water supply and were controlled via the Campbell data acquisition system.

Controllable breakers were programmed to activate connected loads on schedules to simulate human occupancy. The bases for occupancy simulation were data and analysis developed in previous residential simulation activities [15, 16]. Detailed information on the electrical loads used to simulate occupancy and the relevant schedules was reported previously [18].

3.3.3 Hot Water Draw and Draw Profile

PNNL selected a hot water draw and draw profile that was representative of a typical daily draw pattern for a population of homes, rather than a single home and that was feasible to implement reliably and repeatable using existing equipment in the PNNL Lab Homes. The draw profile was based on the U.S. DOE Building America House Simulation Protocols, which specify typical daily draw volumes for different appliances based on the number of bedrooms and an hourly draw pattern based on fraction of total daily load [17, 20][7].

[7] The hot water draw profile in the Lab Homes for this experiment is not shown in this paper but can be found elsewhere [16]

A high hot water draw volume was chosen to create a worst-case scenario to evaluate the maximum space conditioning interaction for the experiments. Therefore, the hot water flow rate was set to 2.0 gpm (7.6 L/minute), for a total draw volume of 130 to 140 gal/day (492 to 530 L/day) in both lab homes.

3.3.4 HVAC System Operation

Throughout testing, the HVAC system in both homes was operated identically. During the cooling season, the 2.5-ton SEER 13 heat pumps maintained an interior set point of 76°F with no setback [17]. During the heating season, the heat pumps were set to “Emergency Heat,” to operate like electric resistance furnaces and maintain an interior set point of 71°F with no setback [17].

3.3.5 Temperature and Humidity Measurements

Identical networks of temperature sensors were deployed in both homes. Each defined area of the home (individual rooms, hallway, and open living areas) had at least one thermocouple; a total of 17 space temperature thermocouples were installed per home.

Two type T thermocouples were installed to measure supply and exhaust process air through the heat pump compressor. Three crawlspace temperature sensors were installed to monitor the temperature of the crawlspace, which was be the temperature of the supply air for the GE GeoSpring HPWH tested in the fully ducted arrangement.

3.3.6 Water Flow Measurements

The water flow rate was measured using a low-flow, impeller-type flow meter with 375 to 1380 pulses per gallon (0.07–5 gal [0.26–19 L] or 0.2–20 gal [0.76–7.6 L] range, depending on the model) with a 6–24 VDC output.

4.0 Testing Protocol

The testing protocol was tailored depending upon the experiment conducted. The GE GeoSpring units were tested over an approximately 2-year period. They were tested for space conditioning (HVAC) during relatively long time periods during the summer (cooling) and winter (heating) in both ducted and unducted configurations. The GE GeoSpring DR experiments were conducted during relatively shorter time periods in the spring and fall.

4.1 Baselining the Homes

Prior to initiating the experiments, the homes were extensively baselined. For experiments 1–4, the homes were baselined with the GE GeoSpring water heaters operating in electric resistance (only) and heat pump (only) modes. For experiments 5 and 6, the homes were similarly baselined although the heat pumps were operated only in heat pump mode as the home thermal/HVAC impacts of the units were not part of the experiment.

4.1.1 Air Leakage

Blower door measurements were taken on both homes as part of the baseline period for experiments 1 and 2 as these (thermal/HVAC impact) experiments depended upon near-identical building thermal characteristics. Air leakage through the building shell was quantified in both homes using a Minneapolis Blower Door Model 3 and DG-700 digital pressure gauge in accordance with ASTM E779, “Standard Test Method for Determining Air Leakage Rate by Fan Pressurization,” and manufacturer recommendations [21, 22].

4.1.2 Null Testing

Following blower door measurements, the homes went through an active null testing period, with full-occupancy simulation to verify equivalent performance. Null testing with full occupancy (lighting, human-related, and equipment sensible loads) and simulated hot water draws showed similar energy use between the two homes, within 1.9 ±2.0% over the cooling season baseline testing period for experiments 1 and 2. The differences in whole-house energy use between Lab Home A and Lab Home B were observed to be within 0.7 ±0.5% over the heating season baseline testing period for experiments 1 and 2.

5.0 Experiments and Results

The results of each of the six experiments described in Table 1 are summarized below. A discussion of those results and conclusions will follow. Recommendations for further investigations follow the discussions and conclusions.

5.1 Experiment #1: Cooling Season HVAC Impact of Ducting the GE GeoSpring HPWH

Over a period of several weeks during the cooling season, both exhaust-only and fully ducted configurations were tested and compared to the unducted unit. Figure 4 illustrates the results of this experiment. Both the exhaust-only (green bar) and fully ducted configuration (red bar) led to increased HVAC energy usage as compared to the HVAC energy use in an unducted HPWH configuration (blue bar). This was attributed to the supplemental space cooling from the unducted HPWH exhaust being available for cooling the homes whereas the cool air was not available in either ducted configuration. The unducted HPWH provided a space cooling benefit equivalent to approximately 1.5 kilowatt-hours per day (kWh/day). Because this additional space cooling is not available in the exhaust-only and fully ducted scenarios, these ducting configurations resulted in increased space conditioning energy use of 9.3 ±1.0% for the exhaust-only and 9.3 ±2.2% for the fully ducted scenario during the cooling season.

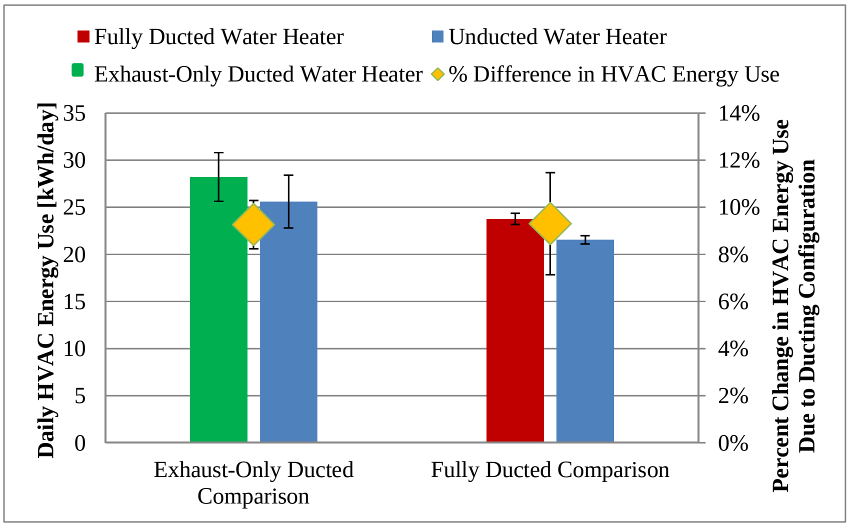

Figure 4. Daily home HVAC energy use and % difference in HVAC energy use for the exhaust-only ducted and the fully ducted GE GeoSpring HPWH experiments in the cooling season.

In Figure 4, the duct configuration (exhaust-only and fully ducted) is compared directly to the corresponding unducted control case (blue bar). The average difference in HVAC energy use during each experimental period is represented by the yellow diamonds, where positive values indicate increased energy use resulting from ducting. The difference in the HVAC energy use for the unducted HPWH between the exhaust-only ducted comparison and the fully ducted comparison periods is due to weather differences during the two discreet time periods of the experiments.

5.2 Experiment #2: Heating Season HVAC Impact of Ducting the GE GeoSpring HPWH

Over a several week period in the heating season, both exhaust-only and fully ducted configurations of the GE GeoSpring HPWH were tested and compared to the unducted unit. The results are summarized in Figure 5. The HVAC energy use in Lab Home A in the exhaust-only ducted configuration (green bar) increased 3.2 ± 2.5 kWh/day, or 4.0 ± 2.8% as compared to the unducted HPWH in Lab Home B (blue bar). The HVAC energy use in Lab Home A in the fully ducted configuration (red bar), decreased 5.7 ± 1.6 kWh/day or 7.8 ± 2.3% as compared to Lab Home B with the HPWH in an unducted configuration (blue bar).

In Figure 5, the ducting configuration is compared directly to the corresponding unducted control case. The average difference in HVAC system energy use during each experimental period is represented by the yellow diamonds, where positive values indicate increased HVAC system energy use resulting from ducting.

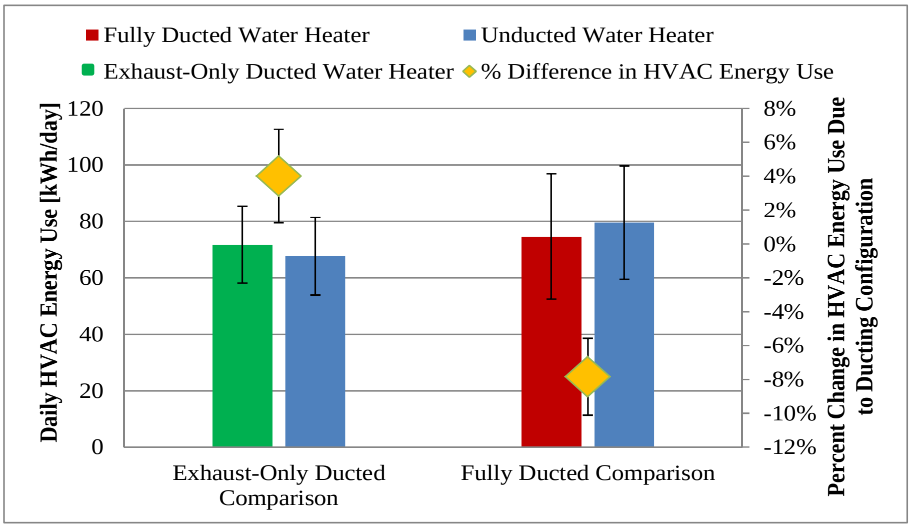

Figure 5. Daily home HVAC energy use and % difference in HVAC system energy use for the exhaust-only ducted and the fully ducted GE GeoSpring HPWH experiments in the heating season.

5.3 Experiment #3: Water Heating Energy Use for Ducted and Unducted Configurations

Ducting can impact the energy consumed by the HPWH as the efficiency of the HPWH will be affected by the temperature of the inlet air. For example, while the unducted water heater may provide space conditioning benefits in the cooling season, such a configuration may increase water heating energy use because the colder inlet air decreases the efficiency of the HPWH. Table 2 summarizes the annualized water heating energy use difference between an unducted HPWH and an exhaust-only and fully ducted HPWH. The energy use difference is calculated based on data taken during the summer and winter experiments and annualized to the Richland, Washington, climate. The measured temperatures during the winter and summer experiments also are shown in Table 2.[8]

Table 2. HPWH energy use for exhaust-only and fully ducted configurations compared to an unducted HPWH.

HPWH Configuration	Energy Use Difference vs. Unducted HPWH	Living Space Average Temperature (season)	Crawlspace Temperature (season)
Exhaust Only	−144 ±74 kWh/yr −6.8 ± 3.5%	75.9 ±2.1°F (cooling) 71.6 ±1.6°F (heating)	Not applicable to this configuration
Fully Ducted	48 ±49 kWh/year 2.3 ±2.3%	74.7 ± 0.4°F (cooling) 71.3 ± 1.5°F (heating)	73.0 ±1.3°F (cooling) 44.2 ±2.2°F (heating)

5.4 Experiment #4: GE GeoSpring HPWH Demand Response Compared to ERWH

This experimental was undertaken to evaluate the DR capability of the GE GeoSpring HPWH as compared to the ERWH under two types of DR events: peak curtailment and balancing reserves (INC

[8] Note that the HPWH energy use difference does not include fan energy used for the exhaust-only and fully ducted configurations.

and DEC, respectively). Table 3 summarizes the DR experiments that were designed to be a range of typical times during which DR may be required across a broad spectrum of utilities.

To implement DR for the GE GeoSpring HPWH, PNNL deployed the built-in capability using the GE Nucleus™, GE's Home Energy Management System, via ZigBee® communication protocol. The mode and tank set points can be controlled through the Nucleus either by a homeowner or a utility employing conserve signals or peak pricing.

Table 3. DR experiments with the GE GeoSpring HPWH compared to ERWH.

DR Experiment	Description	Time of Day	Duration	Purpose of Experiment
AM Peak Curtailment	Turn off heating elements/HP	0700	3 hours	Evaluate HPWH load shedding potential (dispatchable kW and thermal capacity) as compared to ERWH to manage peak load
PM Peak Curtailment	Turn off heating elements/HP	1400	3 hours	Evaluate HPWH load shedding potential (dispatchable kW and thermal capacity) as compared to ERWH to manage peak load
EVE Peak Curtailment	Turn off heating elements/HP	1800	3 hours	Evaluate HPWH load shedding potential (dispatchable kW and thermal capacity) as compared to ERWH to manage peak load
Balancing INC	Turn off heating elements/HP	0200 0800 1400 2000	1 hour	Evaluate HPWH potential to provide balancing reserves for dispatchable kW as compared to ERWH
Balancing DEC	Set tank temp to 135°F	0200 0800 1400 2000	1 hour	Evaluate thermal capacity of HPWH, as compared to ERWH, when temp set point is increased to 135°F (57°C)

Table 4 is a summary of the results of the experiments showing the average water heater power use during the DR event, water heater energy use during the DR event, daily energy use, and the ratio of the HPWH/ERWH for peak curtailment, INC experiment, and DEC experiment.

Table 4. Data from DR experiments for the GE GeoSpring HPWH and ERWH.

Experiment	Duration	Water Heater Mode	Average Power Draw Impact (W)[a]	Average Energy Use During DR Event (Wh)	Average Daily Energy Use Impact (Wh/day)	Ratio HPWH/ERWH
Peak	3 hours	HP	−439	−1,285	−498	2.64

Curtailment[b]		ER	−1,158	−3,320	258	
Balancing INC[c]	1 hour	HP	−442	−442	−159	2.67
		ER	−1,185	−1,185	86	
Balancing DEC	1 hour	HP	220	220	−158	17.1[d]
		ER	1,174	1,174	1,543	

a. Positive numbers indicated increased energy use, and negative numbers indicate decreased energy use.
b. The 0700 peak curtailment event was not successfully implemented because of a communication failure between the GE Nucleus and the GE server. Therefore, the data shown are the average for the combined PM and EVE events. Disaggregated data for the PM and EVE events are available elsewhere [13].
c. Does not include the 0200 event when both water heaters had zero load per hot water draw schedule.
d. Ration range is from 2.12 for the 0200 event to 50.6 for the 0800 event when the HPWH ramping capability in heat pump mode is significantly decreased.

5.5 Experiment #5: Sanden GES-15QTA HPWH Unitary System Demand Response

A DR schedule to simulate an oversupply (peak curtailment) condition and a balancing reserves condition was generated to ascertain the performance of the Sanden unitary water heater and demonstrate the peak shift or reduction associated with each experiment. The peak curtailment experiment is of considerable interest to utilities deploying ERWHs in DR to manage peak demand. Only the oversupply experiment shown in Table 5 is reported. The balancing reserves experiment is reported elsewhere [16].

Table 5. Sanden unitary HPWH oversupply experiment.

Day	Start Time	End Time	Duration (hours)
1	1800	2400	6
2	1700	2400	7
3	1600	2400	8
4	1500	2400	9
5	1400	2400	10
6	1300	2400	11
7	1200	2400	12

As noted in Table 5, the experiment consists of increasing the time the unit is off in 1-hour increments, beginning at 6 hours on Day 1 to a total of 12 hours by Day 7. This increased daily strain on the system was imposed to determine at which hour the system cannot meet the delivered water temperature during the daily draw schedule. The experiment also was designed to determine the load impact from the shift in the HPWH operation. The unit was baselined for 7 days prior to initiating the DR experiments.

Figure 6 shows the water temperature profile for the second DR event (Day 2) where the water heater was off for 7 hours. The corresponding water heater power draw for Day 2 is shown in Figure 7 along with the outdoor air temperature (red dotted line) and crawl space temperature (green solid line). The Day 2 event is shown here as this is the time period during which the hot water temperature drops below the tank set point to about 115°F (46°C) after 6 hours, thus making this demand event resulting in a likely unacceptable water temperature and thus unavailable for residential application.

The sawtooth pattern shown in Figure 6 (and Figure 8) is a result of the temperature monitoring via an insertion thermocouple in a thermowell at the outlet of the mixing valve. As water is drawn, the temperature peaks to the set delivery temperature, a nominal 120°F (49°C), followed by the temperature decay after the draw is concluded. This decay approached ambient temperature (i.e., temperature of the water heater closet) until the next draw occurs at which time the cycel begins again

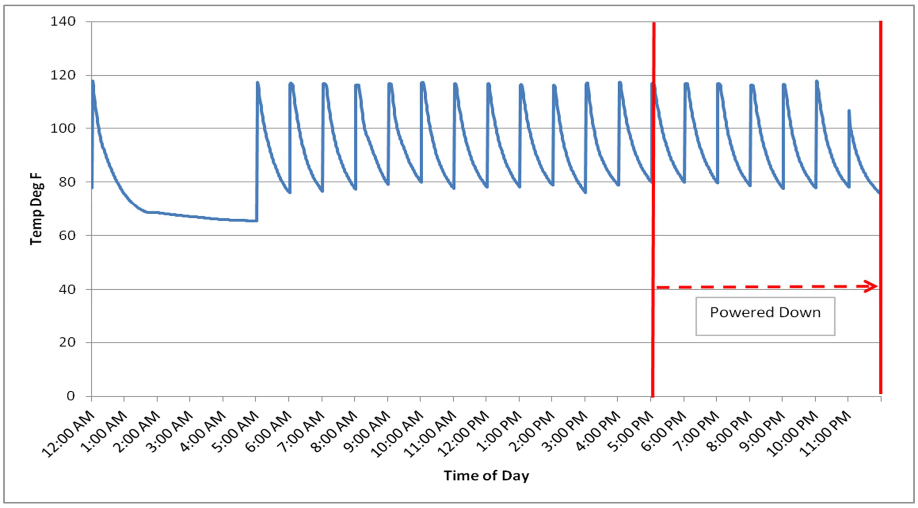

Figure 6. Sanden unitary HPWH oversupply experiment delivered water temperature profile: second DR event (7 hours powered-down).

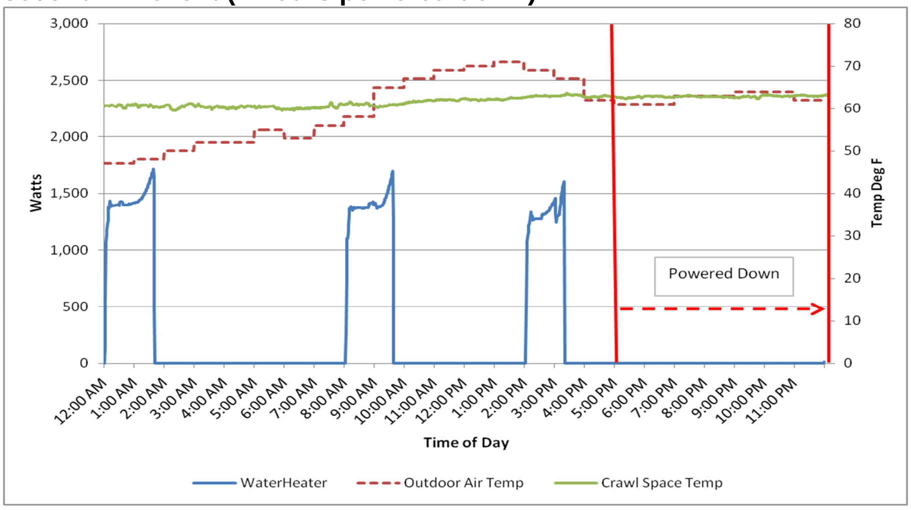

Figure 7. Sanden unitary HPWH oversupply experiment power profile: second DR event (7 hours powered-down).

5.6 Experiment #6: Sanden GAU-315EQTA HPWH Split System DR

The same peak curtailment DR schedule used for the unitary system (Table 5) was used to ascertain the performance of the Sanden split system water heater. The balancing reserves DR experiment schedule for the split system was identical to the unitary system experimental schedule. These schedules are reported elsewhere [16].

The split system was baselined for 7 days prior to initiating the DR experiments. Figure 8 shows the water temperature profile for Day 7 of the experiment when the water heater was off for 12 hours, the longest duration of power-down. The corresponding water heater power draw for Day 7 is shown in Figure 9 along with the outdoor air temperature (red dotted line).

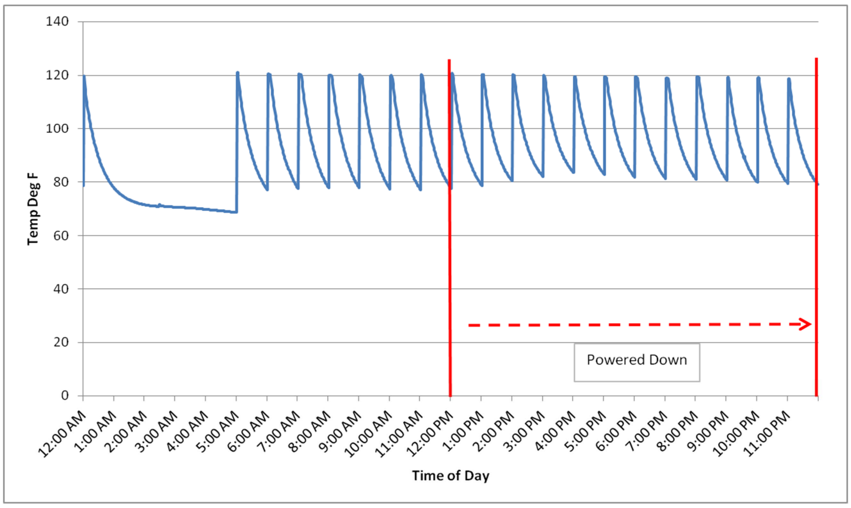

Figure 8. Sanden Split System HPWH Oversupply Experiment Delivered Water Temperature Profile for Last DR Event (12 hours powered-down).

The temperature profile in Figure 8 shows that the delivered temperature still maintains the 120°F values across the DR period because of both the elevated set point and the larger tank capacity. This observation was expected given the size of the storage tank.

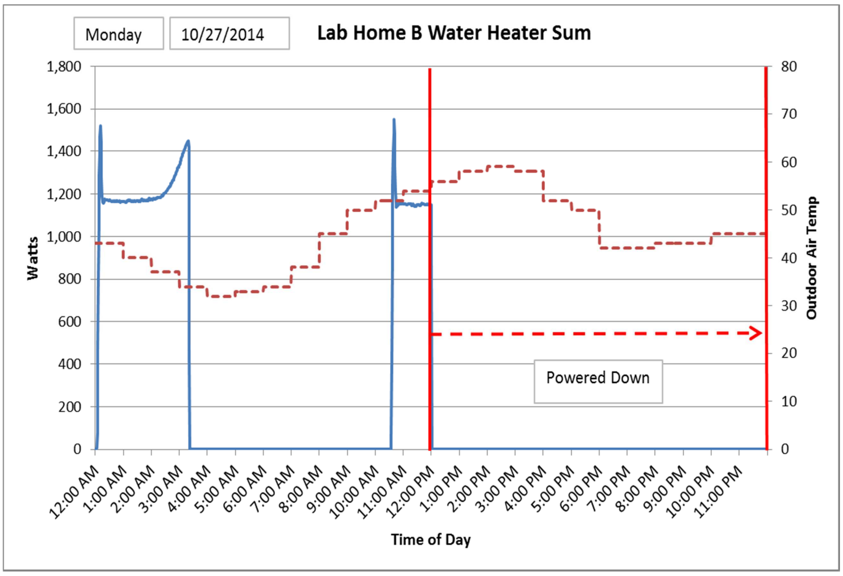

Figure 9. Sanden split system HPWH oversupply experiment power profile for last DR event (12 hours powered-down)

Table 6 presents the summary finding for the oversupply experiments. The Dispatchable Power is the peak watts available to be shifted through oversupply implementation. The Recovery Energy Shift is the value of energy (kWh) that is shifted to the post-oversupply period. The oversupply duration indicates the number of hours the protocol was enacted while still delivering hot water at an acceptable temperature to the household.

Table 6. Summary of the oversupply DR experiments in the Sanden units: dispatchable power, energy shift and off-period delivered acceptable hot water temperature.

Experimental Results	Unitary System	Split System
Dispatchable Power (kW)	1.3	1.2
Recovery Energy Shift (kWh)[a]	2.65	2.95
Oversupply Duration (hours)[b]	6	6
Maximum Off-Period while Acceptable Hot Water Temperature Met (hours)	6	12

[a] The Oversupply Recovery Energy Shift is the water heater energy use at the conclusion of the oversupply period.
[b] The Oversupply Duration of the split system presented was for the 6-hour interval and provided for comparison to the unitary system.

6.0 Discussion and Conclusions

The following is a summary discussion of the experiments and conclusions drawn from the experiment. Experiments 1 and 2 are combined in this discussion because the purpose of those experiments was to determine overall/annual space conditioning (heating/cooling) impact from HPWH ducting. Additional details on the cooling season impact and the heating season impact can be found elsewhere [15].

6.1 Experiments 1 and 2: Whole-House Space Conditioning Annualized Impact of HPWH Ducting

The experimental results were annualized for the climate in Richland, Washington, based on the average number of heating days and cooling days in a year. Specifically, the daily difference in HVAC energy usage for the exhaust-only ducted versus unducted configuration are combined to yield a daily whole-house difference in energy use for that case, assuming all other loads are identical. The annual difference in whole-house energy use for the fully ducted HPWH compared to the unducted HPWH is calculated in a similar manner. The expected annual difference in HVAC and whole-house energy use using this method is shown in Table 7.

Table 7. Comparison of HVAC and whole-house energy use for exhaust-only and fully ducted HPWH configurations vs. an unducted HPWH.

HPWH Configuration	HVAC Energy Use Difference vs. Unducted	Whole-House Energy Use Difference vs. Unducted
Exhaust Only	858 ±440 kWh/yr 6.2 ±3.2%	714 ±446 kWh/yr 2.9 ±1.8%
Fully Ducted	−1,079 ±408 kWh/yr −7.8 ±3.0%	−1,031 ±411 kWh/yr −4.2 ±1.7%

As shown in Table 7, the fully ducted configuration has a significant energy benefit on the HVAC and whole-house energy use (7.8% and 4.2% less energy use, respectively) whereas the exhaust-only configuration has a negative impact on the HVAC and whole-house energy use (6.2% and 2.9% increase in energy use). Also note that the differences for both ducting configurations in HVAC and whole-house energy use is much larger than the difference in water heater energy use (shown in Table 2). The annualized differences in space conditioning energy usage is dominated by space heating, which could be considered a worst-case comparison in this experiment because of the use of an electric resistance furnace for space heating and heat pump for space cooling.

These data can be used to ascertain the cost-effectiveness of ducting (exhaust only or fully ducted) a HPWH taking into account the climate (i.e., degree-days), the cost of ducting, and the cost of energy for water heating and space heating and cooling.

The theoretical annualized differences for exhaust only and ducted configurations also were determined from modeling. Modeling suggests that HPWHs installed in conditioned space will increase HVAC energy use in the heating season because of the use of air that has been initially heated by the HVAC system to heat water and the introduction of cool exhaust air into the space. Therefore, models assume, any heat that has been extracted from the space must be made up, or reheated, by the HVAC system to maintain interior thermostat set points. These models also indicate that exhaust ducting will mitigate the impact of HPWHs on space conditioning systems by preventing cool exhaust air from being introduced into the conditioned space. However, data collected during this experiment suggest that exhaust-only ducting did not decrease space conditioning energy use, as compared an unducted HPWH.

The experimental data may suggest that the reduced HVAC impact is due to buffering of the HPWH space conditioning impacts by the interior walls. For the unducted HPWH, the water heater closet experienced localized cooling while the thermostat, located in the hallway near the kitchen (see Figure 1), was not affected by the HPWH thermal loads. Data taken during the experiments were not sufficient to fully address this observation and further discussions are published elsewhere [14].

6.2 Experiment 3: GE GeoSpring Water Heater Energy Use in Ducted Configurations.

From Table 2, exhaust-only ducting decreased water heater energy use by 144 ±74 kWh/year on an annualized basis. However, this decrease was offset by an increase in whole-house energy use of 714 ±446 kWh/year on an annualized basis (Table 7). Therefore, exhaust ducting in a climate similar to that of Richland, Washington, would not be cost effective. Annualized estimation would be needed for other climate regions to determine overall net energy impacts.

Fully ducting the HPWH resulted in a net increase in water heater energy use by 48 ±49 kWh/yr on an annualized basis (Table 7). However, this increase is relatively small compared to the decrease in whole-house energy use of 1,031 ±411 kWh/year on an annualized basis (Table 7). Therefore, from a whole-house perspective, the net energy impacts of HPWHs installed in conditioned space are driven by the HVAC system interaction and not by the impact of the ducting on the water heater performance.

The magnitude of these energy impacts, their costs and the costs for ducting were determined and reported elsewhere [15]. This analysis suggests that exhaust-only ducting may not be advisable but that full ducting may be cost effective over the lifetime of the water heater in climates comparable to that of Richland, Washington. However, additional analysis would be needed to take these data and develop recommendations for the variety of energy rates, climates, and installations/configurations where HPWHs may be installed.

6.3 Experiment 4: GE GeoSpring HPWH DR Compared to ERWH

Based on the data collected in these DR experiments, both ERWH and HPWH are capable of performing peak curtailment and regulation services. However, their characteristics differ, as can be seen in Table 4 which shows the average impact on power use during the DR event, energy use during the DR event, and daily energy use for ERWH and HPWH for peak curtailment, INC events, and DEC events.

The HPWH provides approximately 38% of the peak reduction or INC balancing response of the ERWH, when accounting for differences in power use and use profiles of the water heaters. The ERWH provides more dynamic response with a large amount of power increase or decrease per water heater. However, the HPWH has longer and more frequent operating times, which means the HPWH is able to respond when an INC event or peak curtailment is needed. In addition, the inherent measured efficiency savings of HPWH (61.7 ±1.7%) compared to a standard ERWH will result in some permanent peak savings as well (not quantified here), resulting in overall peak load reduction for a utility with significant penetration of HPWHs.

However, the DEC response of the HPWH is limited during some parts of the day when especially high hot water use occurs. During the nighttime when there is little to no hot water draw activity, the HPWH has significant capacity to increase load because it takes much longer for increases in tank temperature to saturate, as compared to an ERWH. And, in experiments reported elsewhere [19], a modification to the HPWH control algorithm can allow the HPWH reach tank temperatures above 135ºF (57°C) using only the heat pump mode for overnight DEC response.

With regard to hot water delivery, decreased hot water delivery temperature was measured for all DR events. The most dramatic delivered hot water temperature decrease was ~18ºF (~8°C) for the HPWH during an afternoon peak curtailment event. However, an extremely high hot water draw profile was implemented during these events to provide a “worst-case scenario.” Based on the results of these experiments, decreased hot water delivery temperature is not likely to be an issue for the majority of participants in a DR program providing peak curtailment or INC balancing services even when only the heat pump is used to heat water. A more comprehensive discussion of this experiment can be found elsewhere [19].

6.4 Experiments 5 and 6: Sanden HPWH DR Peak Curtailment

The Sanden split system with the 80 gal (303 L) tank was able to maintain ~120ºF delivered hot water temperature under the relatively extreme DR experiment where the unit was powered off for 12 hours. And, when the DR event was terminated, the ramp up peak power draw was ~1500 W at midnight, thus shifting this peak to a typically off-peak period for most utilities. This is approximately the same peak draw as a standard ERWH (not reported here; see reference [16]). Given the Day 7 experiment profile (Figure 9), it is likely the water heater could provide near 120ºF (49°C) hot water to the home during the initial early morning (0600) hot water draw (~4 gal/hour/~15 L/hr) to later (0700) hot water draw (~11 gal/hr/~43 L/hr) without being powered. This is an advantage of the large tank capacity and flexibility of this unit should a utility wish to avoid an early morning peak. Additional analysis and discussion of the energy impacts of DR compared to ERWH can be found elsewhere [16].

The Sanden integrated system with the 40-gal (151-L) tank was unable to maintain ~120ºF (~49°C) delivered hot water temperature for more than 5 hours after powered off (Figure 6). The delivered water temperature after 5 hours was ~108ºF (42°C) would likely not be acceptable to home occupants. These results were anticipated with a 40 gal tank and were similar to the observation with the GE GeoSpring HPWH DR experiment. However, both the unitary and split systems can effectively recover from peak curtailment up to a minimum of 5 hours in the case of the 40-gal (151-L) unitary system and 12 hours for the 80-gal (303-L) split system. As with the GE GeoSpring HPWH, a utility seeking 3 to 4 hours of peak curtailment and/or peak shifting could successfully deploy the integrated system while simultaneously harvesting the advantage of using less energy to deliver hot water to a home [16].

7.0 Recommendations

Results obtained from the experiments described in this paper answered many questions regarding installation, performance, and DR potential for the current and future generation of HPWHs. Observations made during these experiments also led to questions that could be answered through additional research. These issues and additional research areas include, but are not limited to:

- The GE GeoSpring HPWH demonstration found significant differences between the modeled energy impacts of an unducted HPWH compared to the measured impacts. A more thorough measurement and analysis of air infiltration and movement and temperature gradients inside the home with an unducted HPWH installed in conditioned space needs to be undertaken.

- As delivered, the GE GeoSpring HPWH was not configured for operating with ducting, so the ducting had to be custom designed. A similar study of an unitary HPWH, and perhaps a HPWH with a larger (60-80 gal) tank that was configured for ducting at the factory, may provide additional data on the overall impact of ducting and the optimal ducting configuration for installation in a conditioned space.

- The impact of exterior temperature, water supply temperature, and closet temperature for the Sanden split system on the overall system performance is not well understood. A systematic and controlled evaluation and analysis would be of value given a small number of field research studies have indicated that these variables are not determinative of overall system performance [23].

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Balancing Real-Time Supply and Demand with High Penetration of Renewable Energy: The Case for Grid-Interactive Water Heaters

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Abstract

Over the past decade EU and national policies have dramatically increased the share of electric power coming from renewable sources. In some markets, there is so much renewable energy on the grid that wholesale prices periodically go negative, forcing generators to pay grid operators to take their electricity. Furthermore, the inherent intermittency of these resources has led European utilities to "worry that the growth of solar and wind power is destabilising the grid, and may lead to blackouts or brownouts". The industry is increasingly looking to demand response (DR) resources to integrate the growing amount of intermittent renewables by mitigating the effects of supply fluctuations that make operation of the grid more difficult.

In order to manage this situation, utilities need to maintain increased capability to quickly ramp generation both up and down, which means operating the system at less efficient levels than prior to the growth of renewables. In order to manage this situation and react to rapid fluctuations and imbalances, utilities need to create greater flexibility across the entire system—in terms of both generation flexibility and demand responsiveness. New applications of grid-responsive appliances can help address this issue, providing near instant load curtailment as well as regulation-down services to balance the volatility of many renewable sources of energy.

This paper will present results of several recent and ongoing pilot programs (in Hawaii and elsewhere), as well as document and describe the evolution and growth of the capabilities of grid-responsive electric water heaters. Up to now, the economics of renewable energy have been hurt by the need to address its intermittency, and the grid's inability to accommodate large, rapid fluctuations in renewable supply has created concerns over grid stability. Grid-interactive water heating is shaping up to address both the economic and reliability issues, helping pave the way for affordable, reliable renewable energy for the future.

Introduction: The Problem of High Penetration of Intermittent Renewable Energy on the Electric Grid

Over the past decade EU and national policies have dramatically increased the share of electric power coming from renewable sources. In some markets, there is so much renewable energy on the grid that wholesale prices periodically go negative, forcing generators to pay grid operators to take their electricity. Furthermore, the inherent intermittency of these resources has led European utilities to "worry that the growth of solar and wind power is destabilising the grid, and may lead to blackouts or brownouts". [1]

The industry is increasingly looking to demand response (DR) resources to integrate the growing amount of intermittent renewables by mitigating the effects of supply fluctuations that make operation of the grid more difficult. An acute aspect of this problem is the increase in daily system variability, illustrated by the increasingly irregular "net demand" (customer loads minus self-generation) on the Hawaiian Electric system between 2006 and 2014 (Figure 1). [2] Even the best forecasters and modeling could not have predicted the bending, shifting, and distortion in the shape of that net demand curve, which now carries much greater challenges and risk to the grid operator. That operator is struggling more and more to use traditional utility tools to make generation follow the load.

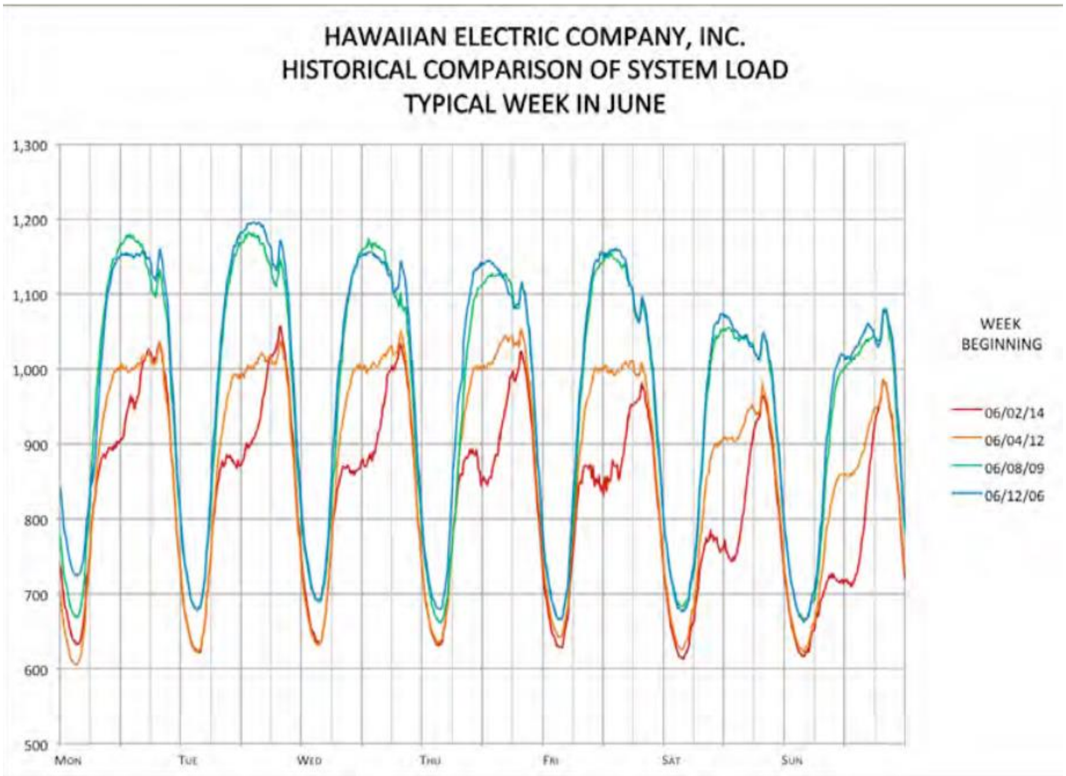

Figure 1 Increasing Irregularity of Net Demand Due to an Increase in Intermittent Renewable Energy
Source: Hawaiian Electric Co.

In order to manage this situation and react to rapid fluctuations and imbalances, utilities need to maintain increased capability to quickly ramp up generation, which means operating the system at less efficient levels than prior to the growth of renewables. However, the issue is not just one of rapid increases in generation—non-renewable generation electric system must also be capable of ramping *down* when the supply of renewables is high. More broadly, utilities need to create greater flexibility across the entire system—in terms of both generation flexibility and demand responsiveness. If generation alone cannot address the issue of intermittent renewables, or cannot do so at reasonable cost, then perhaps demand-side resources can contribute to a cost-effective solution to integration of renewables onto the electric grid.

New applications of grid-responsive appliances can help address this issue, providing near instant load curtailment as well as regulation-down services (via load increases and thermal storage) to balance the volatility of many renewable sources of energy. One such application is known generically as grid-interactive water heating (GIWH) – a technology that can accept control signals from the grid to modulate the power consumption from an aggregations of thousands of electric water heaters via cloud architecture.

In the EU, electric water heaters account for 8.7% of total electricity consumption at 73 TWh in 2009, and the installed stock of electric water heaters in the EU-27 was around 119 million units (out of a total of 267 million units of domestic water heaters, including those using natural gas and other fuels). Roughly 90 million of the units were electric water heaters with storage, while the remainder of the electric units provide instantaneous heating with no storage capacity.[1] If just 10% of these units with storage were equipped with GIWH capability, this could provide up to 20,000 MW of flexible load to support grid stability.[2]

[1] Similarly, in the US, of a fleet of 100 million, approximately 42 million are electric water heaters. [3]

[2] The figure of 20,000 MW of flexible load from GIWH is based on 9 million 4.5 kW units capable, on average, of either an increase of decrease of 2.25 MW.

Load Control with Electric Water Heaters: The Birth of GIWH Technology

According to the 2011 US Federal Energy Regulatory Commission (FERC), Direct Load Control (DLC) programs are the most commonly used type of incentive-based demand response program and are widely available nationally. Approximately 5.6 million customers were enrolled in DLC programs across the nation, and electric resistance water heater programs have become an integral part of the national demand response strategy, operating in 35 of 50 U.S. states.[3]

Peak shaving. Most utilities operate these programs as *peak shaving* DLC programs that primarily curtail water heater load during peak grid conditions. Utility cost savings under such programs primarily can include avoided generation and transmission capacity costs as well as lower energy costs.

Peak shifting. A different utility load management strategy using electric water heaters is *peak shifting*. In these programs, utilities incentivize customers to install water heaters equipped to heat water only during off-peak periods. Since low-cost base load and wind energy generation is typically available at night, sometimes in excess and at negative prices, this strategy is ideal for lowering the overall energy costs of a utility, thereby applying downward pressure on electric rates for the consumer.

With the advent of hourly energy markets and the accessibility to real time market price information in nearly every region of the U.S., advanced storage strategies based on wholesale Locational Marginal Price (LMP) have been implemented. When utilities control the water heater so that it is allowed to charge only when the LMP is low, the water heater will operate at a lower cost than if the unit is operated simply in response to the homeowner's demands for hot water. With access to real-time LMP values, a decision can be made by the utility to charge the unit if the price falls below a certain level and prohibit the charging of the unit if the price exceeds a certain level. A large-volume electric resistance water heater with a smart-grid control unit can be used to implement this strategy. With sufficient storage capacity and fast enough heating capability, the charge level can be determined such that it avoids the problem of running out of hot water as a result control strategy and does not inconvenience the consumer.

Grid-Interactive Water Heaters. GIWH is the emerging consensus term in the US for describing water heaters controlled by real-time, two-way communication with the electric utility, grid operator, or customer aggregation entity. When equipped with grid-interactive controls, an electric water heater can respond to near real-time input by enabling fast up and down regulation and frequency control for the purpose of providing ancillary services and renewable storage to the utility or grid-operator.

In addition to two way communication, GIHWs can measure and transmit information on water temperature, so grid operators know how much energy storage potential the fleet of GIWHs have at any given time; and based on customer usage patterns, they also can judge how much load curtailment, or regulation down service, the fleet can provide while still meeting customers' needs. Through the use of high-storage capacity, highly insulated water heater tanks, GIWH can provide even greater storage and operational capacity/flexibility than traditional water heaters that are simply retrofitted with interactive controls.

Two of the leading U.S. manufacturers of GIWHs have taken slightly different approaches to the technology. As illustrated in Figure 2, one approach is to heat the water in the tank to a temperature higher than standard domestic hot water (DHW) levels (A). The appliance then uses a mixing valve at the outlet to dilute the water, reducing temperatures to DHW levels. An alternative technology preheats the cold "make-up" water at the bottom of the tank to bring it up to standard DHW temperatures (B). The water heater's internal thermostats provide a safety limiter, never allowing the temperature to go over the water heater's setpoint. [5]

[3] DLC programs automatically modify a customer's load via a signal sent by the utility, grid operator, or customer aggregator, requiring no manual intervention by the customer. [4]

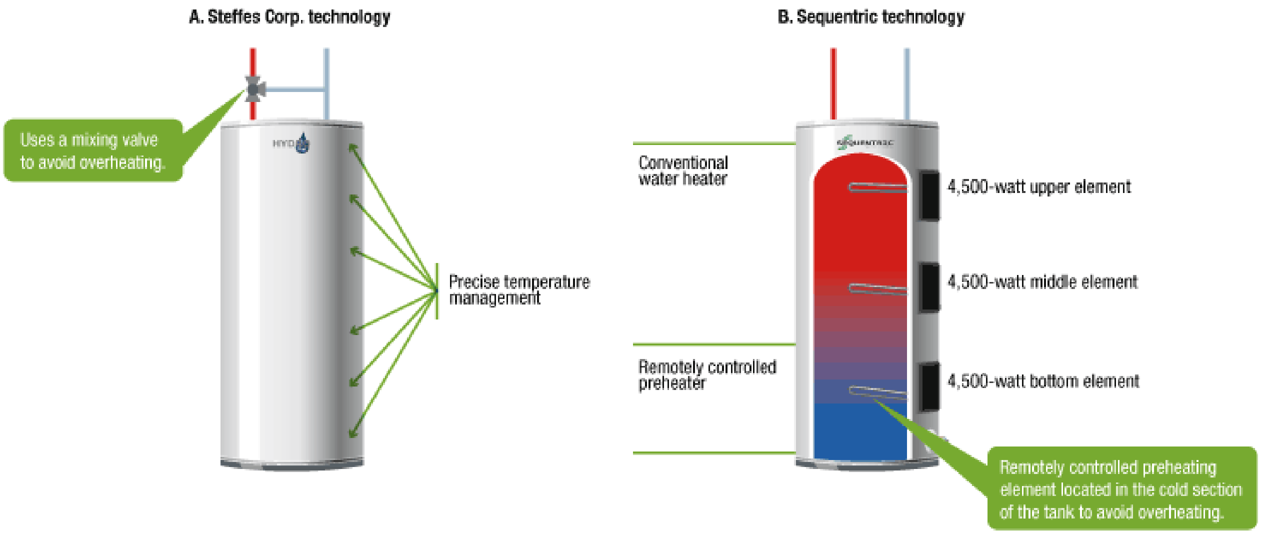

Figure 2. Water Temperature Management Approaches Among U.S. GIWH Controls Manufacturers
Source: Esource

GIWHs go beyond the proven, but limited, historic on/off DR strategy to create a highly flexible energy storage asset, making these devices capable of increasing and decreasing the load on the grid on a second-by-second basis. Unique peak shifting strategies with water heaters have been tested as grid-scale "thermal electric storage", making the technology analogous to a battery. For example, electric grid operators PJM Interconnection and Bonneville Power Administration, controlling large territories on the US east and west coasts respectively, each tested the ability of grid-interactive water heaters to provide controllable load during periods of very low-cost electricity and excess renewable energy generation. [6] In addition, and sometimes simultaneously, the water heaters were able to provide vital grid balancing services in the form of frequency regulation, a service that has traditionally been performed by fossil fuel generators. This service is provided by simple resistance heating elements whose flexibility allows GIWHs to ramp up and down as fast as wind and solar generation can ramp down and up, allowing for improved system control during periods of high renewable energy production. The CEO of grid operator PJM, Terry Boston, said: "Electric water heater storage is the most cost-effective form of energy storage available and has enormous potential to help PJM." [7]

Demonstrating the Effectiveness of GIWH to Support Grid Reliability

The technical feasibility of GIWH is becoming well documented, with trials and demonstrations conducted in a variety of locations by a number of different government and private organizations. Of particular interest to utility operators is the proven effectiveness of GIWH in providing the ancillary services that keep the grid functioning. Several field trials in recent years have provided empirical evidence that GIWH is a viable mechanism for providing grid support. Each of the three trials described below represented a continuing evolution in the sophistication and value of GIWH applications (Table 1).

Table 1. Recent GIWH Field Trials

Host Utility/Trial Name *Location*	**Year(s)**	**Objective of the Field Trial**
Bonneville Power Administration (BPA) *Northwest USA*	2010 to 2013	Demonstration of how certain demand components can be actively managed, altered, and shifted in order to provide grid stability
Hawaiian Electric/ Electric Power Research Institute (EPRI) Hawaii, USA	2013	Evaluation of whether GIWH can provide load control and storage features over various timeframes to be used for renewable integration, load dispatch, and ancillary services.
Power Shift Atlantic (Natural Resources Canada and New Brunswick Power) *Eastern Canada*	2012 to 2014	Demonstrate that load can be adjusted to follow generation through an Intelligent Load Management Solution

Field trial #1 – BPA Balancing Reserves

The Bonneville Power Administration (BPA) in the US Pacific Northwest markets electricity from 31 federal hydroelectric dams and also manages 5,100 megawatts of the world's most tightly concentrated wind generation located on the Columbia River in the State of Washington. The BPA trial, begun in 2010, was designed to show how certain demand components can be actively managed, altered, and shifted in order to provide grid stability via power system balancing services. The trial specifically tested dispatchable GIWH to both increase load when there is extra generation capacity on the grid, and decrease load during peak periods, capacity constraints, grid emergencies or during periods when renewable resources experience intermittency.

Much of the wind on the BPA system has been developed in the same general area, which results in output from much of the capacity tending to move up and down simultaneously, frequently resulting in large, unscheduled swings in wind generation. This causes BPA to increase or back off generation in like amounts in real time to maintain the constant balance of load and generation needed to keep the lights on. Today, BPA provides these balancing services from federal dams. But the hydro system's limits are being reached, and excessive wind generation imbalance is beginning to impose real consequences on power system operation that could affect system reliability.

In the recent GIWH field trial, a signal referred to as "Balancing Reserves Deployed" was employed as a proxy for highly volatile BPA operation system stability requirements. The BRD signal is the difference between predicted wind and actual wind generation in the area. When the BRD signal is positive, it indicates that generation needs to be increased to balance the grid (Up Regulation) and when the signal is negative, it indicates that generation needs to be decreased to balance the grid (Down Regulation). GIWHs can use this signal to shed load when the signal goes high and add load when it goes low. [8] Figure 3 shows rapid, sub-hourly swings in generation requirements of nearly 1,000 MW from a recent snapshot of BPA's deployed balancing reserves dashboard.[4]

[4] BPA provides weekly data on Balancing Reserves Deployed. The data shown in Figure 3 was downloaded from the BPA web site in February 2015.
http://transmission.bpa.gov/business/operations/wind/reserves.aspx

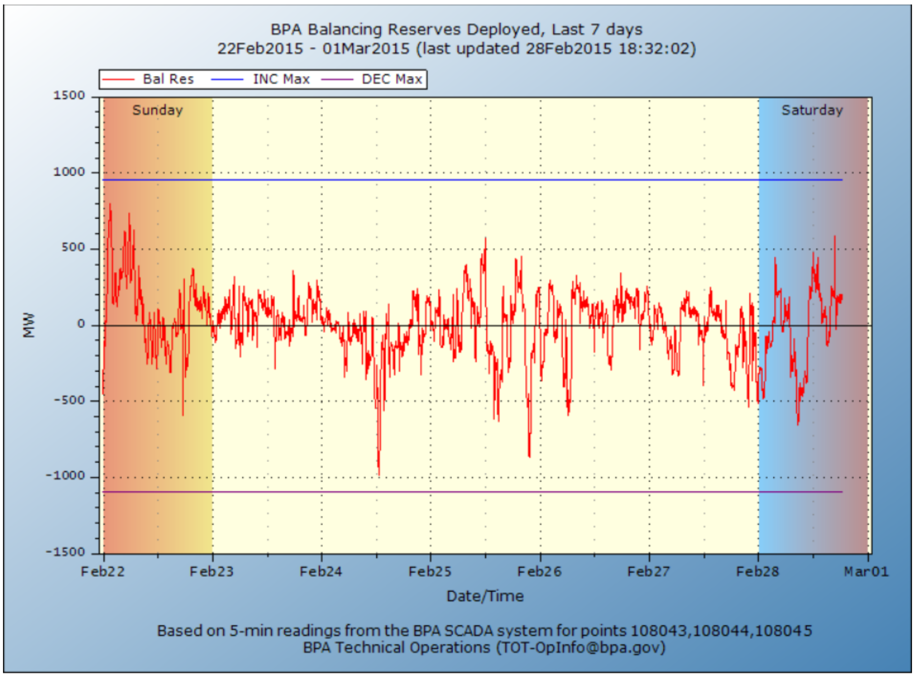

Figure 3 Balancing Reserves Deployed to Maintain System Stability, One Week February 2015
Source: Bonneville Power Administration

One challenge that was immediately recognized during the trial was that individually controlled water heater unit energy consumption was unpredictably volatile. Figure 4 below illustrates how daily usage of an individual unit could vary between near-zero and roughly 25 kWh per day in the summer, and from about 10 kWh to roughly 35 kWh per day in the winter. This variability demonstrated the need to aggregate a large number of controlled water heaters in order to dampen and buffer the individual unit unpredictability and volatility. Through aggregation of many individual loads, the collection of GIWHs would appear and function as a single "virtual asset" that would be quite familiar to the grid operator.

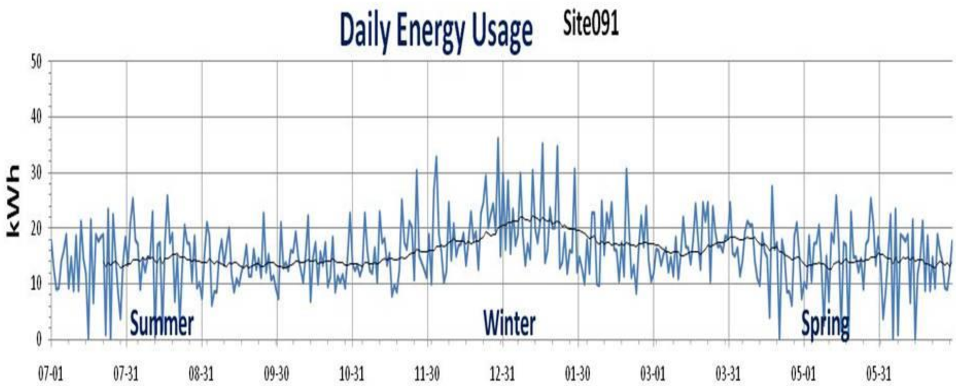

Figure 4. Variability in Daily Energy Usage of GIWH
Source: Steffes Corporation

The project concluded in 2013 and demonstrated the technical feasibility of using GIWHs and other end use loads to provide power system balancing services. Specifically, the trial showed that the participating loads could contribute to power grid needs without being adversely affected, or in cases where end-use needs were degraded; service levels were not reduced at noticeable levels. According to the field study pilot report, "Water heater loads can be served in the process of providing an important balancing service—potentially removing water heater loads from peak demand and load forecasts. The prospect of simultaneously reducing load while providing balancing services is especially enticing." [9]

Field Trial #2 - Hawaiian Electric / EPRI GIWH Responsiveness

The second field was conducted on the island of Hawaii in 2013 at about the time that the BPA trial was concluding. This second trial again used the BRD (supply-demand balancing) signal but this time was specifically designed to evaluate if GIWH could provide load control and storage features over various timeframes and can thus be used in a variety of ways, including for renewable integration, load dispatch, and ancillary services. These field studies provided data on the actual performance of the grid interactive water heaters in customers' homes on O'ahu at the Forest City Military Communities. The Electrical Power Research Institute (EPRI), an independent non-profit research organization, acted as 3rd party verifier.

A key test of the field trial was the speed and accuracy of the GIWH response to requests for power (or curtailment). Figure 5 illustrates how a water heaters is able to match power consumption with a prescheduled load/power profile.

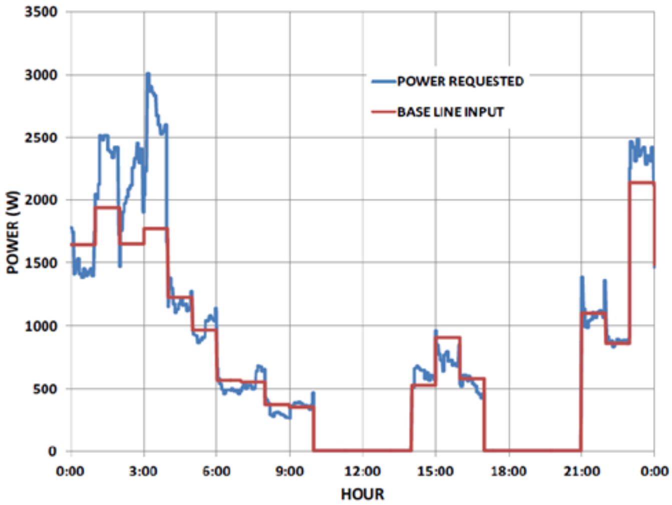

Figure 5 GIWH Responsiveness to Power Requests

In a real-time situation, the responsiveness of GIWHs addresses both the system's need for power and the need for a *decrease* in power (or an increase in load, such as by charging storage reservoirs). Figure 6 illustrates how a GIWH reacts to a request for balancing services (based on the BRD signal) to increase load (draw more power to store hot water) when the BRD signal indicates over-generation, and to decrease load (net positive power flow onto the grid) when the system needs power. The power requested from the GIWH, relative to a scheduled baseline, is a near mirror image of the BRD signal, as is desired (i.e., a positive need for balancing reserves correlates to a negative power consumption for the water heater). Differences in the mirror image are a result of both the lack of precision of GIWH response and also the domestic needs of the customer—such as the demand for water heating in the early evening hours.

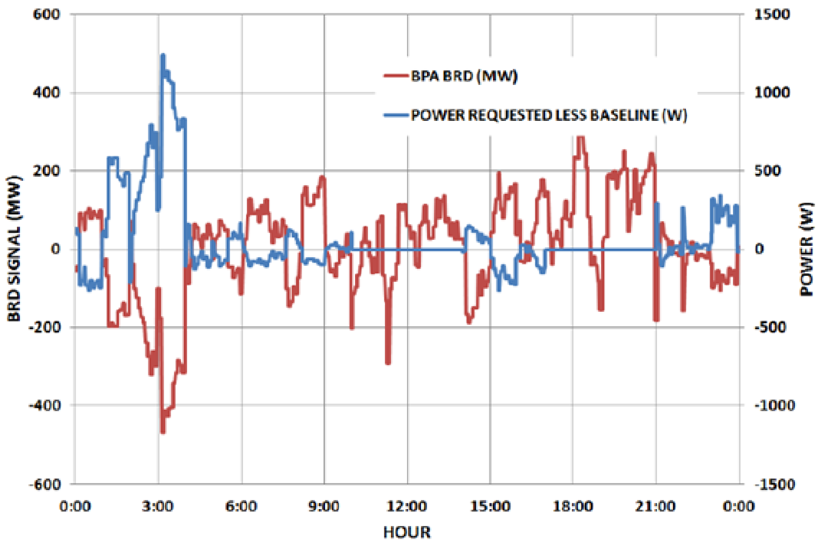

Figure 6. GIWH Power Consumption and Storage in Response to BRD Signals

The field trial demonstrated that if a live stream of SCADA data for wind generation is available, and f forecasted wind information is provided, real time adjustments in power draw from water heaters can account for the wind intermittency. When completed at the end of 2013, the demonstration project provided valuable performance data and information related to customer interfacing of grid interactive water heater technology. [10]

Field Trial #3 - PowerShift Atlantic (Canada)

For more than 2 years, GIWH technologies were involved in a large trial in Eastern Canada called PowerShift Atlantic (PSA), sponsored by Natural Resources Canada (NRCAN) and the Government of Canada's Clean Energy Fund. A key strategic goal of this research and demonstration project was finding more effective ways to integrate wind energy into Provincial electricity systems and in particular that "load can be adjusted to follow generation" by linking Virtual Power Plants (VPP's), aggregators, and various load classes to form an Intelligent Load Management Solution (ILS) to mitigate the effects of the variation of both intermittent renewable generation and load on the system.

Just below is a graph of the capacity, power requested, and load response of that dual space and water heater system during a single day in March of 2014. In that particular case the VPP called on aggregators to absorb an unexpectedly large supply of wind during the night hours preceding this chart which brought the system to a high level of charge in the early morning hours. That thermal energy was then released as comfort heating and water heating during the 5 to 9 a.m. time frame – thereby allowing the aggregated space and water heaters to revert to its nearly 5 MW or power capacity.

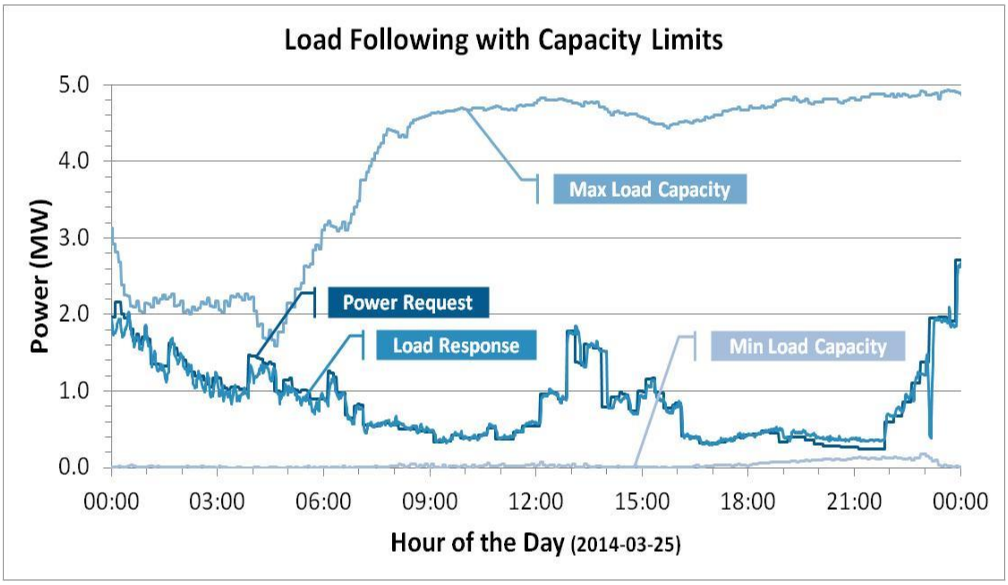

Figure 7. Space and Water Heating System Load Response and Thermal Capacity, 25 March 2014
Source: Steffes Corporation

The PSA demonstration clearly showed that aggregated devices and appliance load could become flexible enough to be made to follow wind and other types of intermittent renewable generation. It also demonstrated that certain systems of aggregated devices could be controlled in near real-time and made to perform higher order grid services.

Conclusions

The GIWH trials conducted to date have demonstrated that when simple water heaters are aggregated and (in particular) enabled with real-time controls, monitoring, measurement, and verification, they can perform in very much the same way and at the speed of a centrally located fast-ramp battery. In ongoing trials certain GIWH technologies are showing that they offer the critical response and real-time controls required for provision of ancillary services, and offer the additional value of grid stabilization and protection from grid collapse caused by severe frequency drop. As growing evidence from both laboratory and field trials indicates, making certain loads more flexible not only accommodates and fosters greater amounts of renewable energy, but going even further and adopting a strategy of "load follows generation" can yield significant operational benefits.

As the state with the highest share of renewable generation among all the 50 United States and as an island with no interconnections to neighboring utility systems, Hawaii is facing grid stability issues unseen in most of the developed world. As a consequence, Hawaiian Electric as the principal electric utility is pioneering the use of new grid-interactive technologies such as electric storage water heaters to help balance the supply and demand of power on a real-time basis. Up to now, the economics of renewable energy have been hurt by the need to address its intermittency, and the grid's inability to accommodate large, rapid fluctuations in renewable supply has created concerns over grid stability. Grid-interactive water heating is shaping up to address both the economic and reliability issues, helping pave the way for affordable, reliable renewable energy for the future in North America and perhaps the world.

While the scale of deployment has so far been limited, the technology is proven and the promise is real. Hawaii is moving toward a scenario of more generation close to load and large amounts of DR capability. If successful in reducing the cost of providing grid stability in an environment of high renewables penetration, this may be a harbinger of things to come on the U.S. mainland and in Europe. In the view of Hawaii Public Utility Commissioner Lorraine Akiba, "We're writing the rest of the world a postcard from the future." [11]

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Utilizing Smart Home data to support the reduction of energy demand from space heating – insights from a UK field study

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Abstract

It is anticipated that the wider deployment of Smart Home systems will give building occupants improved control and automation capabilities over building conditions, services and equipment. These smart technologies will also provide numerous streams of data which could help to identify opportunities to reduce energy demand in homes. This paper explores this topic by focusing on data gathered from Smart Home systems, installed in a sample of five UK homes, which provide occupants with advanced zonal space heating control. Initial results suggest that Smart Home data can generate useful information to assist energy demand reduction; including the identification of excessive heat loss from specific rooms, periods of unoccupied heating, and heating system characteristics that lead to suboptimal heating patterns. Practical issues encountered during the field study highlight important social and contextual factors that can influence the quality of data recorded. These factors could potentially impede the wider adoption of Smart Home technologies with zonal heating functions. This work is continuing and the next steps are to calculate the energy savings which would result after data from Smart Home systems was used to identify inefficient homes, systems or practices.

Introduction

The UK government is committed to achieving a significant reduction in carbon dioxide emissions – an 80% reduction by 2050 in comparison to 1990 carbon dioxide emission levels [1]. It has been estimated that, in 2009, buildings accounted for around 38% of greenhouse gas emissions (by end-use) in the UK [2]. Therefore, measures to reduce energy consumption in buildings are considered as important methods to meet UK carbon reduction commitments [3, 4]. The UK's housing stock is comprised of approximately 27.6 million dwellings which are estimated to be responsible for around 29% of UK energy consumption [5]. Space heating is the largest energy end use in homes, accounting for around 62% of the average UK home's energy use and therefore provides a significant opportunity to achieve energy reductions [5]. At present, efforts to reduce energy demand for space heating in existing dwellings include policy initiatives designed to facilitate retrofits (e.g. the Green Deal), such as thermal upgrades (e.g. loft and wall insulation), more efficient heating systems, and improved heating controls [6]. In regard to the latter, the increased availability of wireless sensors and controls have enabled key elements of the 'Smart Home'[1] concept to be introduced into existing dwellings relatively easily and there is optimism that these technical developments could revolutionize the operation of heating systems; by providing improved efficiently through automation, as well as giving occupants the opportunity to control the use of energy remotely. For instance, recent research suggests that smart zonal heating controls could potentially reduce annual gas demand for space heating by 12% in many UK homes [9]. In addition to smarter controls, the numerous streams of data (e.g. energy and water consumption, environmental conditions, occupancy patterns) from Smart Homes may enable occupants to access more comprehensive and tailored information about daily energy use and information to support retrofit decisions; decisions that offer the long term energy demand reduction through changes made to buildings' built form (e.g. thermal upgrades) [10]. This paper explores this topic by evaluating the type and quality of information that can be derived from Smart Home data to support energy demand reduction in dwellings. More specifically, this paper focuses on technologies that provide advanced zonal space heating control and automation

[1] The term 'Smart Home' is used broadly to describe dwellings that incorporate a variety of information and communication technologies (ICTs), sensor networks and artificial intelligence to gather and utilize data (e.g. regarding occupants, building equipment, the physical environment) to undertake automated actions that optimize building operations and services [7, 8].

capabilities to investigate household heating patterns and opportunities to reduce space heating energy demand. The work draws on data gathered by the REFIT project (see acknowledgements for project details) from an ongoing 2.5 year field study in 20 UK homes.

The next sections provide a brief overview of the types of space heating systems that are typically found in existing UK dwellings. The technologies and methods employed are then described. Initial results from the analysis of sensor data from five UK homes are then presented, followed by a description of practical insights that may influence the quality of data recorded. Finally, the results are discussed and preliminary conclusions are drawn.

UK central heating systems

The most common form of domestic space heating in the UK is from gas central heating systems [6]. At a basic level, these heating systems consist of a gas-fired boiler to heat water, which is pumped to wall mounted radiators in the rooms of the homes (see Figure 1). The system is usually controlled by a programmer/timer (often integrated into the boiler) which allows building occupants to automate heating schedules; modern systems will often allow more complex heating schedules to be set-up for different days of the week. However, the controls also enable occupants to override the heating schedules at any time. When a central heating system is in operation it will pump hot water to the radiators until a predefined temperature is reached. The temperature is frequently governed by a room thermostat (often located in a hallway or living room) which can be adjusted by building occupants; therefore, the temperature of heating throughout the dwelling is determined by the temperature in one location. When the set temperature is achieved, the boiler turns off; however, the pump will continue to propel hot water around the heating system, for a period of time, to ensure that hot water does not stagnate at the boiler. The boiler will only turn back on if the temperature falls below the set point temperature on the room thermostat.

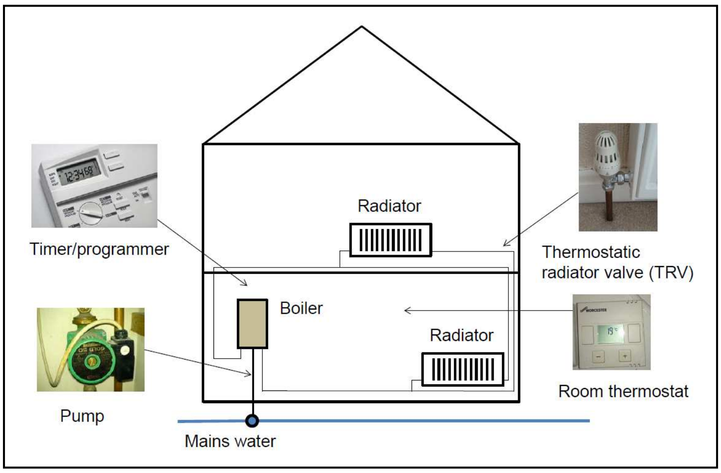

Figure 1: Schematic of a central heating system in a UK home (adapted from [6])

Another common heating control, in many UK homes, are thermostatic radiator valves (TRVs) which control the flow of hot water to individual radiators and thereby control the temperature of individual rooms. TRVs moderate the flow of hot water through the radiator, via a rotating control, by reacting to the local temperature. Although TRVs provide occupants with increased control, the temperature of individual rooms can also be influenced by other factors; such as internal gains (e.g. from appliances), the size of the radiator (i.e. oversized or undersized radiator), heat loss from the physical characteristics of the room (i.e. infiltration rate) and occupant behavior (e.g. window and door opening) [6]. Therefore, individual room temperatures can vary throughout a dwelling and can be very different from the temperature setting of the central heating system's room thermostat. As a result, the collection of Smart Home data about actual temperatures within individual rooms (and the temperature settings made by building occupants) could provide valuable information for energy demand reduction [10].

Methods

Smart Home technologies deployed

A range of Smart Home technologies have been installed in the REFIT project's sample of 20 homes. The procurement process was influenced by key requirements of the project which included: *Functionality* – the project required technologies that would be relatively simple to operate by the householders who have different technical and ICT abilities; *Reliability* – it was essential that the technologies could be relied upon to remain operational (e.g. maintain wireless connection) for the duration of the study. This was not only to ensure the collection of the best quality data possible, but also to minimize house visits to resolve technical difficulties; *Access to data* – remote access to data was important to minimize the number of home visits (a time consuming process to organize and an inconvenience for participants); *Established technologies* – the study sought to utilize existing technologies, widely available for households to purchase. This was partly to avoid technical difficulties with less developed technologies and also to use devices that were representative of those likely to be introduced more widely into UK homes in the short term.

Preliminary testing of a variety of Smart Home technologies was undertaken in test homes prior to the procurement process. However, the testing encountered technical difficulties using a unified system. Therefore, a pragmatic decision was made and two separate systems were installed in each of the study sample homes. These systems provided the homes with real-time feedback information and increased levels of control over the use of electricity, space heating and home security. The first of these systems consisted of Z-Wave Vera3™ controllers [11] connected to Current Cost [12] units which monitor whole house electricity consumption and electrical appliances. Additional Z-Wave smart plugs were installed to enable remote and automated control over connected appliances. The second system, and the focus of this paper, consisted of RWE Smarthome™ devices to control space heating and provide home security features. The details of the RWE system are outlined below.

RWE Smarthome™ system

The RWE Smarthome system provides monitoring and control functions for individual space heating radiators and provides home security capabilities. The system has been developed specifically for the German market by the large German Utility RWE [13]. Key reasons for its use in this study include: its secure and robust wireless propagation (868.3 MHz proprietary protocol); the capability for sensor data to be downloaded remotely from each device; devices can be controlled easily via a computer or laptop with a web browser and /or a smartphone application; and the user interface is comparatively straightforward to use by individuals with relatively limited ICT skills. Figures 2 and 3 show a screenshot of the RWE Smarthome user interface and a range of the sensors installed in the homes, respectively. The 'standard' system procured for each home consisted of the following devices (the number of devices is shown in brackets):

1. Central controller (1): this device communicates with the other RWE devices connected to the system. The device plugs into the back of a broadband router and acts as the gateway for the system's user interface which can be accessed via a computer's web browser and /or a smartphone app).

2. Radiator thermostat (9): the radiator control units allow individual radiators to be controlled remotely or by a rotating control on the device. The device collects data about 'nominal' temperature (i.e. temperature setting nominated by building occupants), 'actual' temperature (temperature measured by the device), and air humidity. When more than one Radiator thermostat is installed in a room (i.e. in rooms with more than one radiator) the devices synchronize so that heating provided by multiple radiators is done in unison.

3. Room thermostats (3): these devices provide an additional physical mechanism to control radiator temperatures in a particular room or zone. Radiator thermostats in a zone automatically synchronize with the Room thermostats.

4. Motion detector (interior) (6): these devices detect movement within a room (detection range of 12 metres). They also have an integrated brightness sensor to detect lighting levels.

5. Motion detector (exterior) (1): this is a weather proofed version of the interior motion detector.

6. Door/window sensor (6): these devices can be attached to a door or window to record opening and closing events.

7. Smoke detector/alarm (1): this device provides basic home security capabilities. The system enables the alarm to be triggered by the motion detectors and/or the contact sensors.

8. Wall-mounted transmitter (2): these wall mounted switches provide participants with physical devices to control the automation profiles set-up on the system. These devices can be fixed to walls and other flat surfaces. Data about their use is not recorded by the system.

9. Remote control (1): similar to the wall-mounted switches, the remote controls provide 8 buttons which can be configured to control the alarm and Radiator thermostats. Data about their use is not recorded by the system.

It should be noted that the RWE system works independently of the boiler and current room thermostat present in the home (it was designed to be ‘plug and play’ and does not require a qualified installer) and consequently there are times when the two sets of heating controls contradict each other. In addition to this although we have good data about the profiles used for individual radiator thermostats, but we do not have the corresponding data about central room thermostats or timer settings.

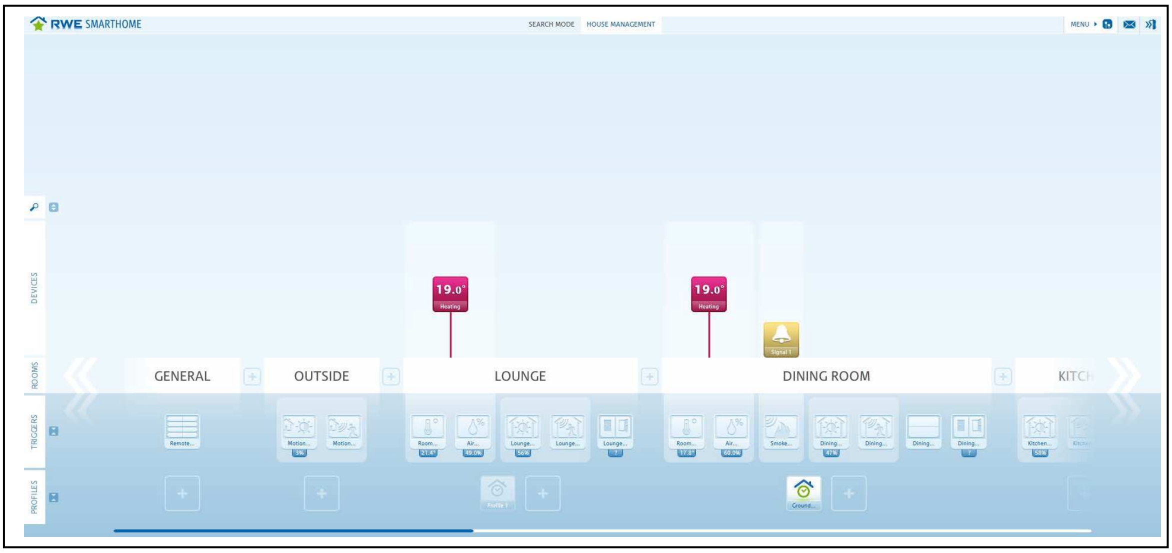

Figure 2: Screenshot of RWE Smarthome user interface via computer web browser

Figure 3: Example of RWE Smarthome devices – (from left to right) Central controller; Radiator thermostat; Room thermostat; Motion detector; Door/window contact sensor; Alarm; Wall mounted transmitter (switch)

The user interface facilitates the remote control of the smart devices and the activation of automation ‘profiles’ from any location, with Internet access, via a smartphone/tablet app or a computer with a web browser. When accessing the user interface via a computer it is possible to set up three main types of automation ‘profiles’: (1) *Time profiles:* enable the individual or multiple radiators to be controlled at designated time periods; (2) *Event profiles:* allow the alarm and radiator thermostats in rooms to be controlled by specified events; for example, using motion detectors to trigger the alarm

(3) *Rule profiles:* logic-based profiles involving one or more conditions; for example, turning a radiator on or off at certain temperature and humidity levels when a window is open. A key feature of the system is that data are collected, managed and stored on a secure database server. These time-stamped data can be viewed via the user interface and downloaded as csv files. This includes ‘actual’ room temperature measured by the radiator thermostats and the ‘nominal’ temperature set by the building occupants. However, only one month’s data are available to be downloaded at any one moment in time; data are continually overwritten so it is essential to download these data regularly or they will be lost. Although not a perfect solution (e.g. the householders’ were required to learn how to use two different user interfaces, no integration between the two systems sensors), it allowed the field study to progress. This approach has also exposed the study participants to different Smart Home technologies and user interfaces, providing valuable data for social science research conducted by members of the project.

Field study sample and installation process

The REFIT project has recruited 20 homes, in the East Midlands region of the UK, to take part in a field study of Smart Home technologies. Five of these homes were selected for this initial data analysis to provide a subsample with different built forms and household types. Table 1 below provides a brief summary of the main characteristics of the chosen homes.

Table 1: Summary of five homes key socio-demographic characteristics

	H3	**H10**	**H15**	**H19**	**H20**
Built form	4 bedroom, detached house	3 bedroom, detached house	3 bedroom, semi-detached house	3 bedroom, semi-detached house	4 bedroom, detached house
Household type	Retired married couple	Married couple, dependent children	Lone parent, dependent child	Married couple, dependent children	Married couple, with non-dependent child
Number of occupants	Two adults (1 male, 1 female)	Two adults (1 male, 1 female), 2 children (male)	One adult (female), 1 child (male)	Two adults (1 male, 1 female), 2 children (male)	Three adults (1 male, 2 female)

The installation of the Smart Home equipment consisted of two key phases. In 2012-13, monitoring equipment was installed in the homes to collected baseline data about electricity and gas consumption and thermal temperatures in the homes. At this stage the Vera Z-Wave system was installed (excluding the *TKBHome* smart plugs) but occupants of the study homes were not given access to the system. In summer 2014, the ‘standard’ RWE Smarthome system acquired by the project (outlined in the previous section) was installed in the homes. The participants were also given access to the Vera Z-Wave system and the smart plugs were installed. Prior to the installation, a face-to-face meeting was conducted with each home to explain the equipment and discuss any concerns. Decisions about the placement of sensors were discussed at this ‘pre-installation’ meeting with guidance from members of the research team; for example, which radiators (if the homes had more than nine) and windows/doors were to have sensors attached. The participants were given the option to have sensors fixed in specific locations (i.e. motion detectors and smoke detectors/alarms are designed to be fixed to walls with screw fittings included with the sensors). In all the 20 homes, the participants requested that the sensors were not fixed in permanent positions at the installation so that they could be given time to experiment with the system and to avoid unnecessary damage to their home’s interior decor. The participants were informed that they could either contact the research team to have them fixed by a contractor or fix the sensors themselves. Only one of the 20 homes contacted the research team to have them fixed in permanent locations and although some occupants fixed sensors themselves, many sensors have remained in ‘unfixed’ locations (e.g. Figure 2 shows a motion detector placed on a shelf). In most of the 20 homes, the installation was completed by the research team. However, on request, some participants were given the opportunity to install some of the equipment themselves; these were participants with higher than average technical abilities and a generally stronger interest in technology. In some cases (e.g. larger houses) extra devices were installed where deemed necessary for research purposes (e.g. extra Radiator thermostats). At least one member of the household was given a brief tutorial of the RWE and Vera Z-Wave systems, during the installation, and made aware of online guidance and instructions. Additional tuition was offered, however, in order to maintain the 'real world' conditions of the field study, the participants were encouraged to attempt to learn how to use the systems themselves.

Data analysis

This paper focuses on data collected during December 2014 from the subsample of five homes and concentrates on four key room types in each home: Kitchen; Lounge (living room); Bathroom; and one Bedroom. All the homes use gas central heating systems as their primary source of space heating. As mentioned previously, the positioning of the sensors was influenced by the number of sensors procured for the project, where the householders wanted the sensors positioned and physical characteristics of the homes (e.g. location of radiators). Table 2 indicates that Houses 3 and 20 did not have radiators in their kitchens. House 20 refrained from having contact sensors installed because they perceived little benefit from the functionality due to having an existing security system. Motion detectors were not installed in any bathrooms or bedrooms. Data were downloaded as csv files from the RWE server (via the web interface) and were processed and analyzed in Microsoft Excel. Data have been manually screened, but a full analysis is yet to be completed.

Table 2: Summary of RWE Smarthome sensors installed in the homes

RWE device	H3	H10	H15	H19	H20
Kitchen thermostat	0	1 radiator, 1 room	1 radiator, 1 room	1 radiator	0
Kitchen motion	1	1	2	1	1
Kitchen contact	1 door	1 door	2 door, 1 window	0	0
Lounge thermostat	1 radiator	2 radiator, 1 room	1 radiator, 1 room	1 radiator, 1 room	1 radiator, 1 room
Lounge motion	1	1	1	1	1
Lounge contact	1 door	1 door, 1 window	2 window	0	0
Bathroom thermostat	1 radiator	1 radiator	1 radiator	2 radiator	1 radiator
Bathroom contact	0	0	0	1 window	0
Bedroom thermostat	1 radiator, 1 room	1 radiator	1 radiator, 1 room	1 radiator	1 radiator, 1 room
Bedroom contact	2 window	0	0	1 window	0

Where 'heating period' values are presented (e.g. the average room temperature when a radiator is set to provide heat by an occupant), "cut off" temperatures were used, based on the occupants settings of the room and radiator thermostats, to determine periods of heating. For example, Figure 4 shows temperature data recorded in House 10's kitchen by the RWE system and shows that two internal room temperature values are recorded: 'nominal' – the temperature setting nominated (i.e. set) by occupants; and 'actual' – the room temperature measured by the sensor(s). Although the radiator is set at 15°C for the majority of the day, in this case the radiator's heating period would be considered to occur during the 19°C periods, in the morning and evening, and a "cut off" temperature of 16°C would be used. Figure 4 also illustrates a limitation of the system; it can be seen that the actual temperature dips below the nominal temperature in the morning and that the radiator is not on in the evening heating period. This is because the central heating system's boiler has been turned off by the programmer or room thermostat which is not controlled by the radiator thermostats. It is also apparent during the midday hours that an additional source of heat (e.g. a heat gain from cooking or solar radiation) and/or heat from another room is resulting in a temperature increase despite the radiator having been turned off. Future work will conduct a detailed analysis of the data for the 20 homes over the full heating season. Internal temperature data are also being recorded in each of the dwellings' rooms with Hobo temperature data loggers to provide comparative data for the future analysis, these temperatures will also enable the RWE temperatures to be assessed for uncertainty, however, this data was not available at the time of publication. Consequently, there is still some uncertainty regarding the validity of the results and their interpretation must be done with caution, that said, much of the discussion of this paper is focused on heating patterns and not relative temperatures and therefore the data is still insightful.

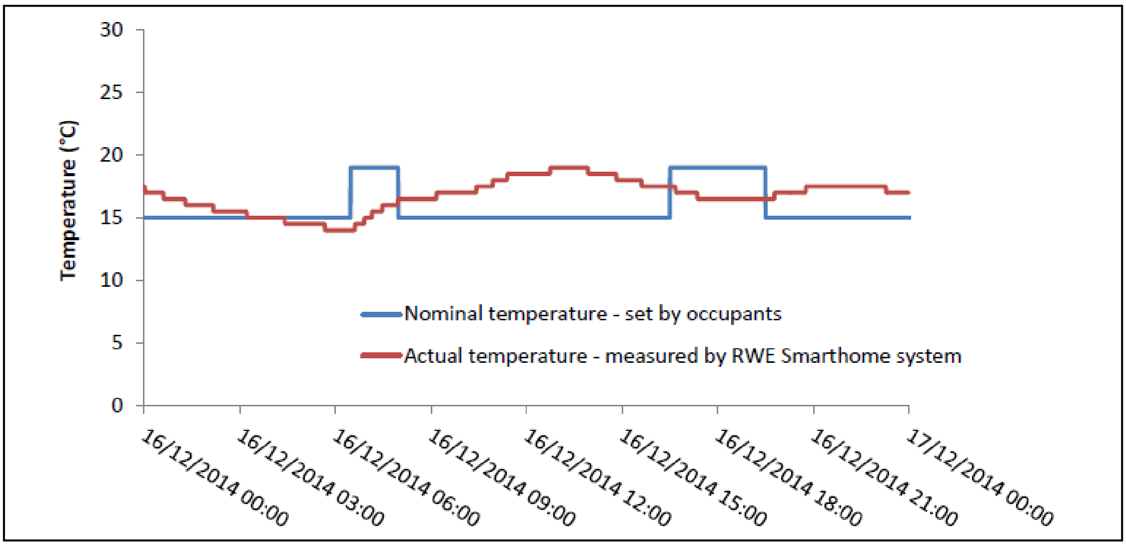

Figure 4 – Example of temperature data from the RWE system at House 10 showing nominal (or nominated) and actual (measured) temperature in a single room on the 16th December 2014

Initial results

This section provides results from the initial analysis of 'real world' data recorded at the five homes, in December 2014, for the kitchen, lounge, bathroom and a main bedroom. The first section provides average values for the heating periods (i.e. room temperature when a radiator is set to provide heat). The second section provides example profiles to illustrate potential opportunities for energy demand reduction that can be derived from Smart Home data.

Average internal room temperatures

Table 3 provides average values for 'nominal' (the setting nominated by occupants) and 'actual' (measured) internal room temperatures. It is apparent that the overall average values for the actual temperatures in the sample's kitchens and bathrooms fall below the nominal temperatures set by the occupants. In two kitchens (House 10 and House 15), the temperature is around 2°C lower than the nominal temperature. It is not possible, at this stage of the analysis, to definitively explain the differences between nominal and actual temperatures in these rooms, however it is of interest as it highlights the disconnect between the settings that occupants use and what actually happens. For example, House 10's kitchen is a large space (connected to a hallway) and this built form may prevent the room's radiator from heating this space effectively, particularly during periods of cold external temperature. In House 15, the nominal temperature of the kitchen radiator thermostat was set continuously at 21°C but the heating system was rarely able to heat the room to this temperature. House 15's bathroom, which particularly influenced the overall average values, had its nominal temperature set continuously at 26°C; this temperature was well above the boiler's room thermostat setting. Consequently, the nominal temperature was never reached and the radiator valve was continuously open. As a result, opportunities to use the RWE system to reduce periods of ‘unnecessary’ heating in House 15’s bathroom were not undertaken by the occupants. The range of nominal and actual temperatures shown in Table 3 also indicates a significant amount of variation which is not clear from the average values alone. In order to gain a deeper insight the following section explores the data in more detail.

Table 3: Average and range of nominal (as set by the user profile) and actual internal room temperatures recorded during heating periods

	H3	H10	H15	H19	H20	Average
Kitchen nominal (°C)	N/A	19.2 (30.0-19.0)	21 (21.0-21.0)	18.0 (21.5-14.5)	N/A	19.4
Kitchen actual (°C)	N/A	17.4 (20.5-12.0)	17.3 (21.5-13.5)	18.5 (24.0-8.0)	N/A	17.7
Difference (%)	N/A	90.6	82.4	102.8	N/A	91.2
Lounge nominal (°C)	19.0 (22.0-19.0)	19.0 (26.0-17.0)	20.4 (26.5-19.0)	17.9 (22.0-12.5)	18.5 (22.0-17.0)	19.0
Lounge actual (°C)	19.4 (22.5-13.0)	19.3 (22.0-15.0)	18.1 (24.0-14.0)	18.3 (26.5-10.5)	19.2 (23.5-16.0)	18.9
Difference (%)	102.1	101.6	88.7	102.2	103.8	99.5
Bathroom nominal (°C)	19.0 (19.0-19.0)	18.0 (20.0-18.0)	26.0 (26.0-26.0)	17.0 (23.5-15.0)	18.5 (22.0-18.0)	19.7
Bathroom actual (°C)	18.0 (21.5-14.5)	18.4 (22.0-13.5)	18.1 (24.0-12.5)	17.6 (23.0-14.5)	18.8 (25.0-14.5)	18.2
Difference (%)	94.7	102.2	69.6	103.5	101.6	92.4
Bedroom nominal (°C)	19.0 (19.0-19.0)	19.1 (30.0-19.0)	17.7 (22.5-16.0)	17.3 (21.5-15.0)	13.7 (30.0-12.0)	17.3
Bedroom actual (°C)	17.6 (20.0-14.5)	19.6 (23.5-13.0)	18.3 (23.5-15.0)	17.3 (23.0-6.5)	16.0 (21.0-6.5)	17.8
Difference (%)	94.2	102.6	103.4	100.0	116.8	102.9

Space heating profiles

The manual screening of the Smart Home data and the production of profiles to explore patterns of space heating led to identification of some potential opportunities to reduce energy demand and improve occupants’ thermal comfort. The significance of these potential opportunities to energy reduction in the homes is yet to be fully understood; for example, the initial analysis does not take account of external temperatures, but the examples highlight areas where there is energy saveing potential.

Heating system characteristics – set-point overshoot and heating lag

Figure 5 provides a simple example of a 24 hour heating profile for House 10’s bedroom gained with the data from a radiator thermostat; the nominal temperature in this example was automated through the use of the RWE systems’ ‘Time’ profile function. It is clear that the room temperature remains above the minimum 15°C nominal setting for the 24 hours and that the humidity in the room generally decreases as actual room temperature increases. Importantly, the actual temperature in the room is often above the 19°C maximum setting during heating periods; this is when the residual heat within the radiator continues to heat the room despite the radiator valve being turned off. Analysis of other rooms in this dwelling suggests that the morning heating period (set using the timer on the boiler) is around two hours, so some of the additional heat which continues to make the room overheat could also be from other rooms. However, the ‘set-point overshoot’ in this room suggests that the occupants may also be able to reduce their energy use by altering the nominal time periods to focus the heating when it is required (i.e. account for the heating after the valve is turned off) or by reducing the nominal temperature setting (e.g. from 19°C to 17°C) which may be able to reduce the effects of the set-point overshoot.

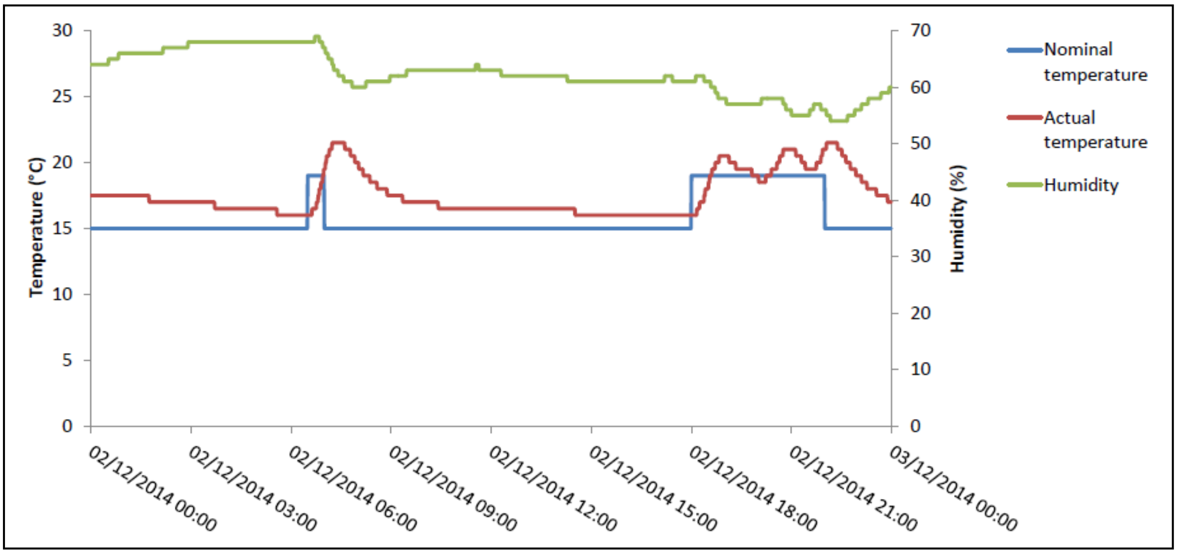

Figure 5: Heading profile recorded by RWE Smarthome system for House 10's bedroom on the 2nd December 2014

It is also apparent that there is a delay, or 'heating lag', between the radiator valve turning on and the room reaching the nominated temperature (i.e. the time taken for the room to increase from the 15°C to 19°C nominal temperature). An optimized start would help this but is not available in the system used here. This is particularly pronounced for the heating period between 0630 and 0700 where it can be seen that the room only reaches 19°C at around 0700 and the temperature continues to rise until it reaches a peak of 22°C (3°C higher than the nominal temperature) an hour after the nominal temperature is set to 15°C. In terms of thermal comfort, the occupants may need to incorporate the heating and cooling lags into their use of the RWE system to ensure their nominal temperature is met for the entire time period. Occupants may already be taking this heating characteristic into account because the time it takes to heat up the room would be similar to the use of conventional heating controls. Data regarding the thermal comfort of the occupants or information about why they turn their heating on at certain times were not collected; consequently, the research team is unaware whether the occupants are incorporating the heating characteristics into the automation. If the occupants are unaware, then this simple feedback could help them to improve their thermal comfort. A less complex solution, from the occupant's perspective, would be to introduce more intelligent control capabilities into the Smart Home system's automation (i.e. control algorithms) so that the system can respond to the heating system characteristics (i.e. set-point overshoot and heating lag) to meet occupants nominal settings automatically. This increased intelligence would save energy and would be more intuitive for the user.

Identifying excessive heat loss

The previous example highlighted that feedback could help occupants understand how their heating system operates in a particular room. Further insight can also be gained by examining the rate at which the actual temperature increases and decreases. For instance, in Figure 5, the relatively rapid rate at which the room heats in the morning may indicate that the heating system is functioning efficiently. In contrast, the rate at which the heat is lost from the room may indicate whether the room is sufficiently insulated. For example, Figure 6 shows a 24 hour heating period for House 19's lounge which uses the RWE system's 'Time' profile function to automate the room's heating. The temperature in this space did not drop significantly during the night and the morning heating period may be unnecessary given that the room appears to retain the heat throughout the day. This slow rate of heat loss (relative to the other dwellings shown here) may indicate that the room is well insulated; assuming that no additional heat source is being used or that these measurements were not taken on a mild day. Interestingly, the actual temperature during the evening heating period does not reach the nominal temperature set by the occupants and there is a slow rate of temperature increase. This is a pattern that often appeared in the month's data for this room. This could suggest that there may be a regular 'temporary' form of heat loss (e.g. an internal door or a window is open) or that the heating system is unable to respond and provide the level of heat required by the occupants – i.e. the radiators are undersized for the space or a radiator is not working correctly (e.g. flow of water is inhibited by residue). A conversation with one of the occupants highlighted that the installer of the radiator had reservations that it was not large enough to heat the space; however, the occupants preferred the slim dimensions of the radiator and progressed with its installation.

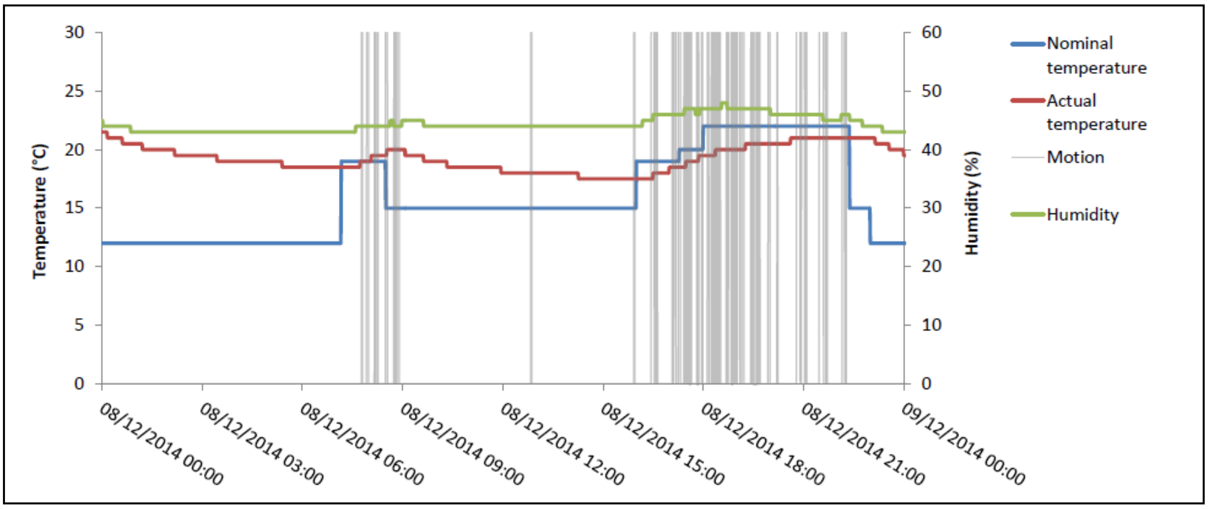

Figure 6: Heating profile recorded by RWE Smarthome system for House 19's lounge on the 19th December 2014

Figure 7 shows a 48 hour heating profile for House 3's lounge; the RWE's 'Time' profile function used to automate the nominal temperature is clearly discernable. Similar to the bedroom at House 10 (see Figure 5), there is a 'set-point overshoot' leading to measured temperatures, during heating periods, being in excess of the temperature nominated by the occupants. A 'heating lag' is also observable which leads to a delay in the room reaching its nominal temperature. The adjustment of the automation (i.e. reduce the nominal temperature and period of heating) could potentially improve occupants comfort and/or reduce the amount of energy used for heating the room. However, in contrast to House 19 (see Figure 6), the faster rate of heating and heat loss may indicate: (1) the heating system is performing efficiently in the room (i.e. reaching the nominal temperature quickly); (2) thermal upgrades (e.g. insulation, draught excluders) or changes in occupant behavior (e.g. closing internal doors) could be an opportunity to reduce the rate of heat loss and retain heat in the room.

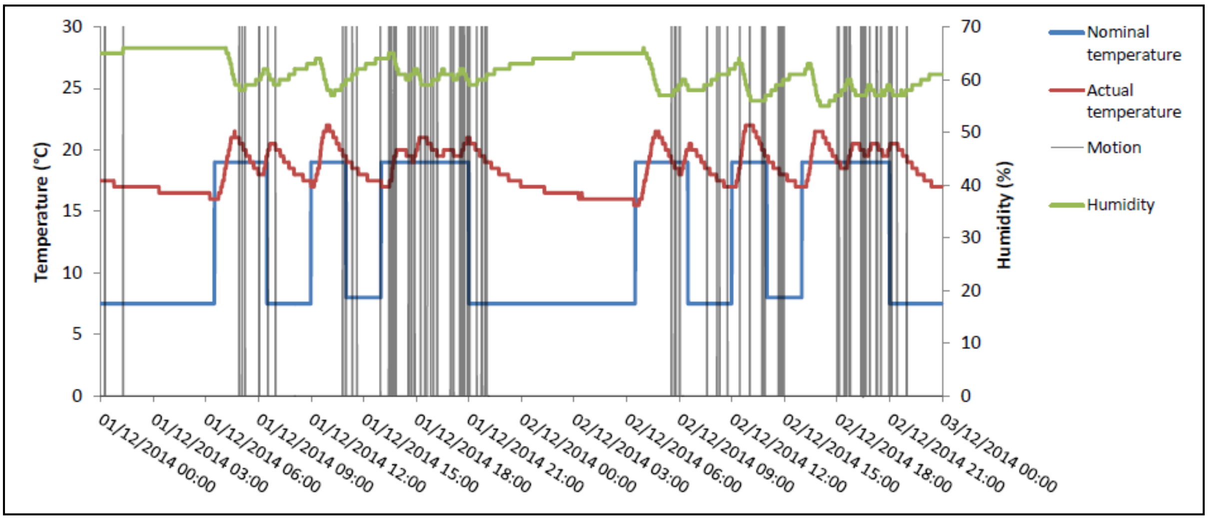

Figure 7: Heating profile recorded by RWE Smarthome system for House 3's lounge on the 1st and 2nd December 2014

These potential opportunities are not clear from the average values shown in Table 3 (nominal and actual values are similar for both House 3 and House 19 and could easily be interpreted to indicate both rooms are performing efficiently). However, as will be discussed later, any interpretation of the information must be done carefully as other contextual issues may be influencing the data recorded.

Unoccupied heating

Figure 6 and 7 also provide information about occupancy patterns gained from motion sensors. The general occupancy recorded in House 19 (Figure 6) fits relatively well with the automation profile. The main unoccupied heating occurs from around 07:10 to 07:50 which may be time factored into the profile due to the delay in the room reaching its nominal temperature. Although not excessive, data from House 3 (Figure 7) provides an example of periods of heating without occupancy in the room – e.g. early afternoon on 01/12/2014 – and potential opportunities to reduce energy use. However, this is a complex issue because it takes time (numerous hours in some cases) to heat a room to the nominal temperature. Therefore, it is not always possible to heat a room only when it is occupied. Nevertheless, it is possible to identify heating periods which are regularly unoccupied and, as above, this data could be used by occupants to change their heating practices and alter automation settings.

Contextual factors and limitations of sensor data

Although the above figures may infer information about the characteristics of heating systems and/or potential opportunities for energy saving, the examples also highlight the need to understand the context in which data is collected. For instance, the built form of House 3 may play an important role for the observed patterns of heating (see Figure 7). In this dwelling the lounge is connected to the dining room by an opening that contains a two sided fireplace; consequently, the temperature in the lounge will be influenced by the flow of air from other parts of the building. Further influences on the lounge's internal temperature relate to the positioning of furniture in the room and other 'energy saving' devices. Figure 8a shows that a sofa next to the radiator which may influence the flow of air from the radiator and that a 'radiator booster' has been installed by the occupants – a battery powered device used to increase the circulation of warm air from the radiator. Another factor reported by householders, was the drying of clothes on radiators (see Figure 8b). These examples highlight that to gain a more complete understanding of the data recorded by Smart Home systems, it is essential to appreciate other contextual factors that may exist in a home. Thus, simple interpretations of data must be viewed with caution.

Figure 8a and 8b: Examples of contextual influences on radiators – (left) House 3's lounge radiator with a sofa in close proximity and a battery powered radiator booster; (right) Radiator covered by large bath towel at a study home

Another limitation to the analysis relates to the number of sensors installed in the homes. For example, Figure 9 shows a heating profile over 24 hours in House 3's main bedroom located on the first floor; it is apparent that the same RWE 'Time' profile applied to the lounge (see Figure 7) is used to automate the heating of the bedroom. The actual measured temperature remains relatively constant throughout the day suggesting that the room retains heat efficiently. However, it is apparent that there is a difference of around 0.5°C between the nominal and actual temperatures; this may be measurement error and will be investigated in future analysis (previous studies have reported sensor uncertainty at approximately 0.5°C [6]). Without occupancy data for this room (a motion detector was not installed in the bedroom) it is not clear how often the room was occupied during the day but the opening and closing of a window indicates some activity. An observable decrease in internal room temperature occurs when the bedroom window was open. Despite installing contact sensors in the majority of the homes, the initial data analysis has experienced difficulties linking door and window opening events directly to temperatures in the building. In addition, the contact sensor shown in

Figure 9 provides no indication of how wide open the window was during this period; important data if attempting to evaluate the thermal characteristics of the room.

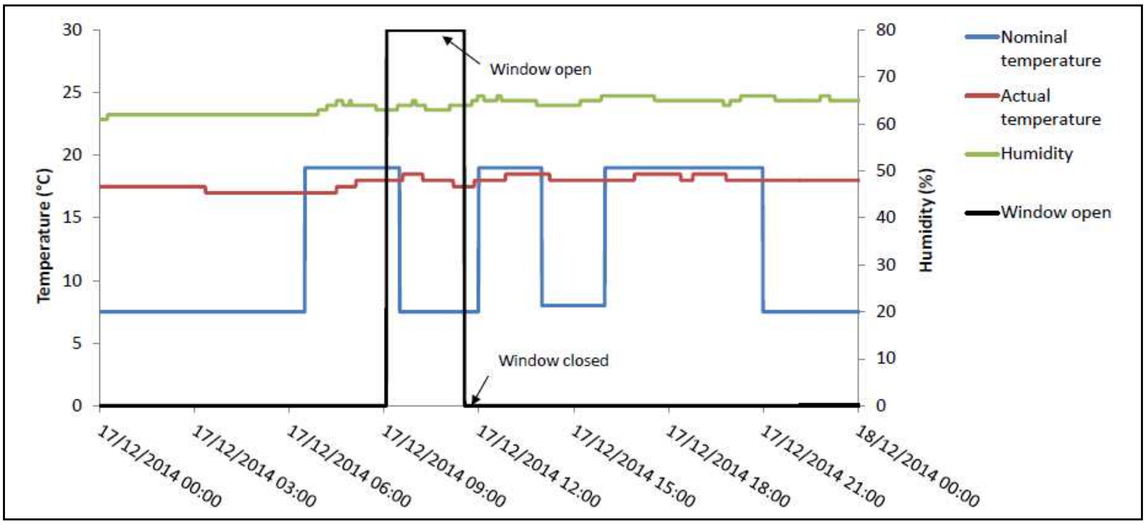

Figure 9: Heating profile recorded by RWE Smarthome system for House 3's main bedroom on the 17th December 2014

The limited number of contact sensors installed in each individual home (n=6) means that it is impossible to know whether other windows and internal doors are open or closed over a given period and thereby influencing the temperature measurements recorded. To gather these data would require all windows and internal and external doors to be monitored. Furthermore, the use of motion detectors in all rooms would enable a more detailed assessment of unoccupied heating in each room. This installation approach was too expensive for this study to undertake and highlights that comprehensive sensor installations would enable a better interpretation of the data to be made.

Practical insights

The previous section has highlighted that contextual issues need to be understood in order to gain a more complete understanding of Smart Home data. The practicalities of conducting the field study reflect this finding and in some cases such issues have significantly influenced the quality of data gained from the Smart Home systems. For instance, a limitation associated to the use of the RWE system in the UK (the system was designed for use in German dwellings) was the lack of data gathered about occupants' control of boilers and associated programmers and room thermostats; these data would provide a much more comprehensive understanding about patterns of heating but as stated above are not available for this analysis. The accuracy and precision of the measurements recorded by the 'off the shelf' equipment is also fundamentally important and still to be assessed; poor accuracy could lead to incorrect interpretations and result in inappropriate (and potentially counterproductive) decisions being made to reduce energy demand. As mentioned previously, the majority of the motion detectors were not positioned in fixed locations which presents the possibility that devices could be moved by participants or obstructed by household objects. Importantly, the maintenance of the RWE system relies on occupants replacing batteries in the sensors, performing software and firmware updates, and managing the occasional loss of wireless communications. The neglect of this type of maintenance has occurred in some of the 20 homes during the study, often due to individuals' limited technical knowledge or lack of engagement with the Smart Home systems. As a result, these issues have led to periods of less that optimal data in some of the homes (e.g. sensors not in operation).

Social and contextual issues could also influence the adoption of the technologies. Using Smart Home systems appears to require much higher levels of engagement from building occupants, in comparison to the use of standard TRVs, and occupants will likely require new technical skills to manage Smart Home systems. Many existing building infrastructures will also likely require infrastructural upgrades. The field study often experienced limited access to Ethernet sockets on routers (and available mains power sockets) due to exiting ICT equipment in the dwellings. Importantly, many of the homes required upgrades to their heating system's radiator valves which were often old and/or defective (e.g. corroded, immovable valve pins) or incompatible with the RWE radiator thermostats (e.g. radiator valves of low manufacturing quality were often incompatible). The replacement of these valves required the services of a plumber at 13 of the 20 homes; on average the cost was around £545 for each of the 13 homes. This additional cost to the purchasing a Smart Home system may present too higher price for many homeowners.

Conclusions

The initial results presented in this paper suggest that data from Smart Home systems have the potential to inform attempts to reduce energy demand from the use of space heating. The examples used in this paper illustrate three potential areas where data from the increased uptake of Smart Home sensors could be used to show where energy can be saved in homes.

(1) *Heating system characteristics – set-point overshoot and heating lag*: these characteristics resulted in rooms being heated to higher temperatures and for longer than the automation set by the occupants. A more accessible and user-friendly form of feedback (e.g. web application) could help occupants to evaluate their heating patterns more easily and optimize their automation profiles accordingly. Alternatively, as Smart Home heating controls become more 'intelligent' the systems will learn to account for these characteristics so that occupant's automation profiles are heated without human intervention; (2) *Identifying excessive heat loss*: the rate of heating and cooling observed from the temperature data could potentially be used to assess heat loss and inform thermal upgrades (e.g. insulation, draught excluders, etc.) or behavior change (e.g. close windows or internal doors). In terms of thermal comfort, these data could also be used to assess the performance of a heating system (e.g. whether radiators are a sufficient size to heat a space or malfunctioning). In the UK, products are now available that use algorithms to estimate a dwellings insulation levels and the performance of its heating systems based on the rate of changes in internal temperature (see [14]). Similar algorithms could be developed to assess the performance of individual rooms within a dwelling. (3) *Unoccupied heating* – although a complex issue, it is possible to identify heating periods which are regularly unoccupied. This information could be used by occupants to change their heating practices or use technologies to automatically reduce heating periods based on occupancy patterns.

The initial results also suggest that without the widespread installation of sensors (e.g. all windows, internal doors, occupancy in all rooms) a comprehensive understanding of influences on a home's heating patterns cannot be gained – i.e. the data can raise as many questions as answers, perhaps a more pertinent question is what are the most important things to measure in a home? Importantly, the work suggests that the evaluation of Smart Home data requires an understanding of social and contextual influences on space heating within a dwelling (e.g. ventilation behavior, built form, etc.). If Smart Home data were used to inform retrofit decisions, by an independent advisor, it would be essential to involve the occupants in the assessment process. The quality of data provided by Smart Home systems is also fundamentally influenced by social and contextual factors (e.g. sensor placements, maintenance of the system, etc.) and such issues may have the potential to influence the wider adoption of Smart Home technologies (e.g. the financial cost of upgrading heating systems). It has been highlighted elsewhere that research into Smart Homes has frequently taken a technological standpoint [15]. Further research is required to explore the Smart Home concept from a user perspective; this is an approach that the REFIT project is pursuing through ongoing research. Future work also intends to develop analytical techniques to conduct a more systematic evaluation of this dataset which will include an assessment of the energy saving potential of the systems installed and where these systems could be improved with more intelligent controls.

Acknowledgements

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Operation and profitability enhancement of micro- and nano-CHP systems in residential buildings using home automation

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Abstract

The deployment of combined heat and power (CHP) systems in residential buildings has large potential for energy and CO_2-emission savings. In recent years, a large number of new nano- and micro-CHP systems in the power range between 1 kW_{el} and 5 kW_{el} have been introduced into the marked. Although investment costs have declined considerably, most micro-CHP systems that are operated in classical heat-led operation still can hardly compete with state-of-the-art heating systems like gas condensing boilers.

In this paper we examine the potential for profitability enhancement of nano- and micro-CHP systems in residential buildings by on-site energy management, i.e. by measures that aim at phasing the electricity and heat generation of the CHP system to the electricity and heat consumption of the building. In a first step, preparatory analyses revealed that the rate of electricity self-consumption is the most important parameter for the economic feasibility of nano- and micro-CHP systems in residential buildings: the CHP unit can only be operated profitably when a certain level of electricity self-consumption is exceeded. Profitability enhances when the rate of self-consumption increases.

Hence, the condition for the classical heat-led operation of the CHP unit – a sufficiently low temperature in the buffer tank – is complemented by a second mandatory condition for operating the CHP unit: sufficient electricity demand in the building. In order to realize the novel ‘electricity-oriented’ operation mode of the CHP unit presented in this paper, the operating times of the CHP unit are additionally shifted towards the hours with highest electricity consumption in the building. Furthermore, the output of CHP units designed for power modulation is adjusted according to the electricity and heat demand of the building and, potentially, also according to external requirements by the network operator or the control centre of a virtual power plant.

In addition to optimizing the operating time and power output of the CHP unit, electricity self-consumption can also be enhanced by shifting the operating time of flexible household appliances like washing machines and dishwashers. By means of a cost-effective home automation system, flexible loads are turned on when the CHP unit is operating and part of the generated electricity is fed into the grid.

Finally, the classical heat-led operation of the CHP systems was analysed in the buildings under evaluation in order to identify in each building the specific potential for enhancing operation and

profitability. Based on these analyses, an individual energy management strategy is devised for each building under evaluation. Generally, the analyses reveal that the challenges for different types of buildings and CHP systems differ considerably: in multi-family homes (MFH) with micro-CHP system, the home automation system mainly makes use of the possibility of power modulation. The integration into a virtual power plant as well as making use of the thermal inertia of the building for an advanced heat management are important aspects of the energy management strategy.

On the other hand, in single family homes (SFH) or end-terrace houses (TH) with nano-CHP system power modulation is not possible. Hence, the operating times of the CHP unit have to be shifted to the times of highest electricity consumption.in these buildings. The necessary flexibility for the operation shift is gained from the heat storage capacity of a 750L buffer tank which is installed in all buildings. Furthermore, flexible household appliances are turned on/off by means of plug adapters by the home automation system according to the current energy situation of the building. The current level of electricity generation, consumption and feed-in is displayed via an app or website to the residents so that they can run their electrical appliances in order to increase electricity self-consumption and, thus, the profitability of their nano-CHP system.

1. Introduction

Combined heat and power (CHP) systems convert the chemical energy of a fuel more efficiently into useful energy since heat and electricity generation are combined in one plant. In other words, in CHP systems the heat which is released in the process of electricity generation is used for space heating. Hence, there is large potential for fuel and CO_2-emission saving when conventional heat and electricity generation plants on the basis of fossil fuels are replaced by CHP systems. The application of modern micro- and nano-CHP systems on the basis of natural gas is the least CO_2-intensive way of using fossil fuels. Moreover, in the long-term the fossil natural gas can be replaced by bio natural gas (biomethane) originating from two possible sources: biogas purification and the power-to-gas process.

Micro- and nano-CHP systems which are installed in residential buildings as an 'electricity-generating heating system' consist of two major components:

- a CHP unit – for the combined heat and electricity generation as described above – and
- an auxiliary heating unit which assures sufficient heating power on cold winter days.

The auxiliary heating unit is usually a conventional gas condensing boiler which is only used when the CHP unit is not able to provide sufficient heat to the building. CHP units can be classified into nano- and micro-CHP units according to their output power. In this paper, CHP units with a rated electrical power below 2.5 kW_{el} are referred to as 'nano-CHP units' and the larger CHP units above this threshold are referred to as 'micro-CHP units'.

The Federal Government of Germany aims at increasing the percentage of CHP at Germany's total electricity generation from today's 15% to 25% in the year 2020 as one important action for achieving Germany's climate protection targets. [1] Therefore, since April 2012 the purchase of micro- or nano-CHP systems is promoted by the Federal Office of Economics and Export Control (*BAFA – Bundesamt für Wirtschaft und Ausfuhrkontrolle*) with an investment grant. The investment grant is graded according to the electrical power rating of the CHP unit and starts at 1,900 Euro for 1 kW_{el} systems. Moreover, also the Federal Land of North Rhine-Westphalia promotes the purchase of CHP systems below 20 kW_{el} with an investment grant starting at 1,425 Euro for 1 kW_{el} systems. [10] Beyond the investment grants, combined heat and power generation is promoted in Germany by a CHP bonus of 5.41 cent for each kWh of generated electricity as well as the refund of the energy tax for the consumed natural gas.

Despite these incentives, most micro- and nano-CHP systems can hardly compete with state-of-the-art heating systems, like gas condensing boilers, when they are operated in the classical heat-led operation mode. In this mode, the CHP unit is operated like a conventional heating system – and sometimes referred to as 'electricity-generating heating system' – according to the heat demand of the building. However, the profitability of the CHP system rises when it is operated in such way that a higher percentage of the generated electricity is consumed on-site within the building.

Furthermore, there are major changes in the German energy sector – both technically in the energy system and economically in the energy market – due to the ongoing German energy transition (‘Energiewende’) which also affect considerably the operation and profitability of CHP systems. The major general trends are as follows:

- In the electricity network
    - the demand for base load electricity declines whereas
    - the demand for flexible electricity generation grows.
- At the European Energy Exchange (EEX), the average price for base load electricity has decreased considerably from ~ 50 € / MWh in the period 2005–2008 to ~ 30 € / MWh in 2015. [20] The average base load price – also referred to as ‘CHP index’ – is the compensation that is paid to the CHP operator for the electricity feed-in by the CHP system.
- The electricity price for private households (electricity purchase from the electricity provider) has increased considerably.

Hence, the revenues of micro-/nano CHP systems operated in classical heat-led operation – the compensation for the electricity feed-in into the grid – have dropped considerably. On the other hand, the economic advantage of electricity self-consumption has risen considerably. Consequently, there is large potential for profitability enhancement when the electricity (and heat) output of the CHP system is matched to the electricity demand of the building in order to increase the rate of self-consumption.

As mentioned above, with increasing shares of fluctuating electricity generation from wind and solar power in the electricity system also the demand for flexible balancing energy increases continuously. Micro-CHP systems can provide balancing energy since their power output can be modulated promptly and in principle they can be switched on/off at any point of time. Hence, micro-CHP systems can be operated in ‘electricity-oriented’ mode which potentially also takes into account the requirements of the electricity system and, thus, balance the fluctuating electricity feed-in from renewable energies. Providing balancing energy as well as purposefully feeding in electricity at times of high electricity prices – especially when several micro-CHP systems are interconnected to a virtual power plant – are promising ways to obtain additional revenues and to enhance the profitability of the micro-CHP system.

A study which was published recently by the think tank ‘Agora Energiewende’ also states that the role of CHP systems will change considerably in the course of the German energy transition: besides generating heat and electricity, CHP systems should also provide and be paid for system services and flexibility (balancing power) in the national electricity grid. [18]

2. Scope and approach of the research project

2.1. Scope

The research work presented in this paper was carried out within the research project “From laboratory to demonstration: CHP pilot project for CO_2 reduction in the InnovationCity Bottrop” whose goal is to halve the CO_2 emissions by 2020 and to improve the quality of life in the pilot area. [2]

In the city of Bottrop 100 innovative micro- and nano-CHP systems were installed in existing residential buildings by the project coordinator Gas- und Wärme-Institut Essen e.V. (GWI). [3] Out of these, 10 buildings were selected by Ruhr West University and GWI for an in-depth study of the CHP system and its interaction with the building.

2.2. Research approach

As a first step, the economic feasibility of the different micro- and nano-CHP systems that take part in the field test is examined by means of a full cost accounting in chapter 4. The operation of the respective CHP system is evaluated in comparison to a conventional reference heating system – a state-of-the-art gas condensing boiler with η_{th} = 95% – and electricity purchase from the local electricity provider. The economic evaluation is based on the economic and regulatory conditions in the energy market in Germany in the year 2015 and shows that the percentage of electricity self-consumption is by far the most crucial parameter for enhancing the profitability of micro- and nano-CHP systems in residential buildings.

Based on these results, for each CHP system is worked out from an economic point of view under which conditions the CHP unit and under which conditions the auxiliary heating unit should be operated in order to supply the heat demand of the building in the most economical way.

In chapter 5, the status quo of the user and building behaviour (profiles of the heat and electricity consumption) as well as the performance of the CHP systems in the classical heat-led operation are analyzed within the investigation period from December 2014 to June 2015 which covers winter, spring and summer months.

These results are used in order to identify the potential for CHP operation and profitability enhancement in different seasons of the year (chapter 6). The objective is to devise an individual on-site energy management strategy for each type of building and CHP system.

First of all, the classical heat-led operation of the CHP system is to be replaced by a novel '**electricity-oriented CHP operation**' which includes the following requirements and measures:

- a sufficiently low temperature in the buffer tank
- assuring that a minimum level of electricity self-consumption is reached, i.e. the CHP unit is run only in periods with (on average) sufficient electricity demand in the building
- to shift the operating times of the CHP unit towards the hours with highest electricity consumption in the building (in order to maximize electricity self-consumption) and
- to modulate the electricity and heat output of the CHP unit (if power modulation is possible)

Secondly, various options for on-site energy management are evaluated in chapter 6 that aim at further matching the electricity and heat generation (of the CHP system) to the electricity and heat consumption (of the building) as well as gaining greater flexibility for the electricity-oriented operation of the CHP unit. Important aspects of a sophisticated energy management strategy are advanced buffer tank management and, where appropriate, including the entire building mass as a huge heat reservoir into the heat management of the building.

Finally, the energy management is realized by means of a home automation system which allows for

- automatically switching on *(off)* the CHP unit according to the current electricity consumption in the building,
- controlling and regulating the room air temperature individually in each room – in this manner, also the temperature of the walls and floor slabs can be indirectly influenced for the sake of including them into an advanced heat management and
- desactivating the radiators in a room when a window is detected as open and
- the integration of the CHP unit into a virtual power plant.

3. Building characteristics, CHP characteristics and measurement data

3.1. Building and CHP characteristics

The evaluations presented in this paper are based on a field test of 100 micro-CHP systems in the city of Bottrop, out of which 10 CHP systems were selected for further analysis. They are installed in 10 residential buildings of the following types:

- 3 Multi-Family Homes (MFH),
- 6 Twin-Houses or End-Terrace Houses (TH) and
- 1 Single Family Home (SFH).

Data recording has started in 2014 and continues until the end of the heating period 2015/16. The measurement data is recorded by GWI and provided as raw data to Ruhr West University. Due to incomplete measurement data in 4 of the buildings, it was decided to restrict the analyses carried out in this paper to the 6 buildings whose characteristics are displayed in Tab. 1. The characteristics of the respective CHP systems are listed in Tab. 2. The investigation period, reaching from December 2014 to June 2015, contains a complete winter period (Dec – Feb), a complete spring period (Mar – May) and the month of June which represents a summer month.

Building characteristics

ID / Building type	CHP	Year of construction	Living space [m²]	No. of residents
TH1	EcoGen WGS 20.1	1988	176	2
TH2	EcoGen WGS 20.1	1988	120	3
TH3	EcoGen WGS 20.1	1956	145	4
TH4	Vitotwin 300W	1919	160	2
SFH	ecoPower 1.0	1903	168	2
MFH	ecoPower 4.7	1960	400	15

Table 1: Basic characteristics of the 7 buildings evaluated in this paper (TH = twin-house or end-terrace house, SFH = single family home, MFH = multi-family home). [3]

Characteristics of the CHP systems

Manufacturer, CHP designation	Power modulation	Engine	η_{el} [%]	$P_{el,CHP}$ [kW]	$P_{th,CHP}$ [kW]	$P_{th,aux}$ [kW]
Brötje, EcoGen WGS 20.1	No	Stirling	13.5	1.0	3.4 – 5.6	5.2 – 13.3
Viessmann, Vitotwin 300W	No	Stirling	13.5	1.0	3.6 – 5.7	5.9 – 19.5
Vaillant, ecoPower 1.0	No	Otto	26.3	1.0	2.5	2.4 – 16.0
Vaillant, ecoPower 4.7	Yes	Otto	24.6	1.5 – 4.7	4.7 – 12.5	5.9 – 35.0

Table 2: Basic characteristics of the CHP systems installed in the field test in Bottrop. [6], [7], [8], [9]

η_{el} Electrical efficiency of the engine
$P_{el,CHP}$ Electric power of the CHP unit
$P_{th,CHP}$ Thermal power of the CHP unit
$P_{th,aux}$ Thermal power of the auxiliary heating unit

3.2. Measurement data

3.2.1. Brötje and Viessmann CHP systems

The arrangement of the basic components and the points of measurement for the Brötje and Viessmann CHP systems are displayed in Fig. 1. For both manufacturers, the CHP unit and the auxiliary heating unit are combined in one apparatus (for the Vaillant systems see Fig. 2).

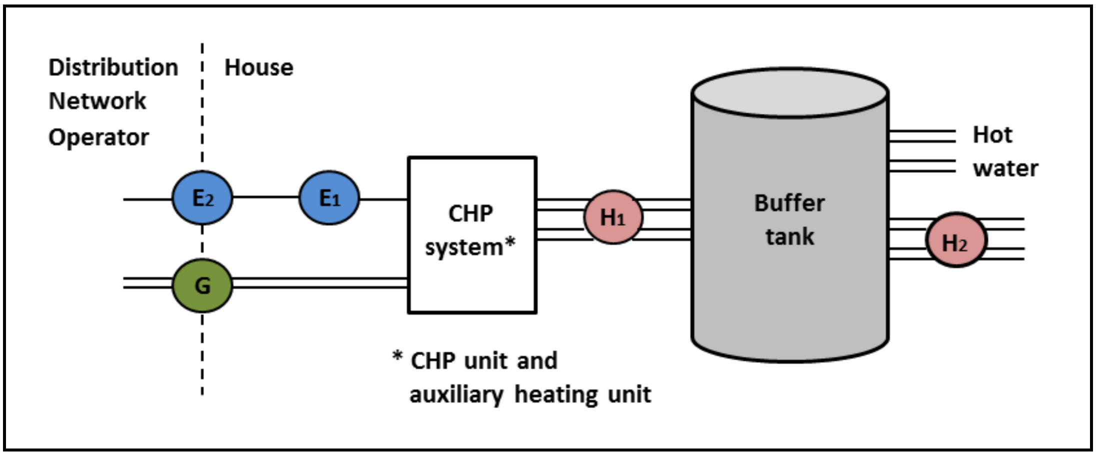

Figure 1: Arrangement of the basic components and the points of measurement for the Brötje and Viessmann CHP systems. Cf. [3]

The heat meter H_1 measures the heat generation of the entire CHP system which is fed into the buffer tank. At the outlet of the buffer tank the second heat meter H_2 measures the heat quantity which is supplied to the heater circuit. Both heat meters record values only in the coarse resolution of 1 kWh. Therefore, all hourly heat outputs referred to in this paper are specified in kWh/h instead of kW.

The gas meter G is able to record the standard volume of the natural gas (by converting the gas volume at operating conditions into the gas volume at standard conditions). The standard gas volume is converted into energy by the conversion formula according to [3]. The higher heating value (HHV) of the natural gas is taken from the local distribution network operator's notification about the gas quality of each month within the Bottrop area. [4]

The electricity which is generated by the CHP unit is measured by the electricity meter E_1. The second electricity meter E_2 is installed at the household electricity meter of the network operator and measures both the electricity fed into the grid and the electricity drawn from the grid. The electricity consumption of the building is the sum of E_1 and E_2 where E_1 is the CHP electricity generation and E_2 is the electricity drawn from the grid minus the electricity fed into the grid. All electricity values are recorded at a temporal resolution of 5 minutes.

3.2.1. Vaillant CHP systems

In the Vaillant CHP systems, the CHP unit and the auxiliary heating unit are not combined in one apparatus as shown in Fig. 2. Both units are equipped with a heat meter so that the heat generation of the CHP unit and the auxiliary heating unit, respectively, are recorded separately.

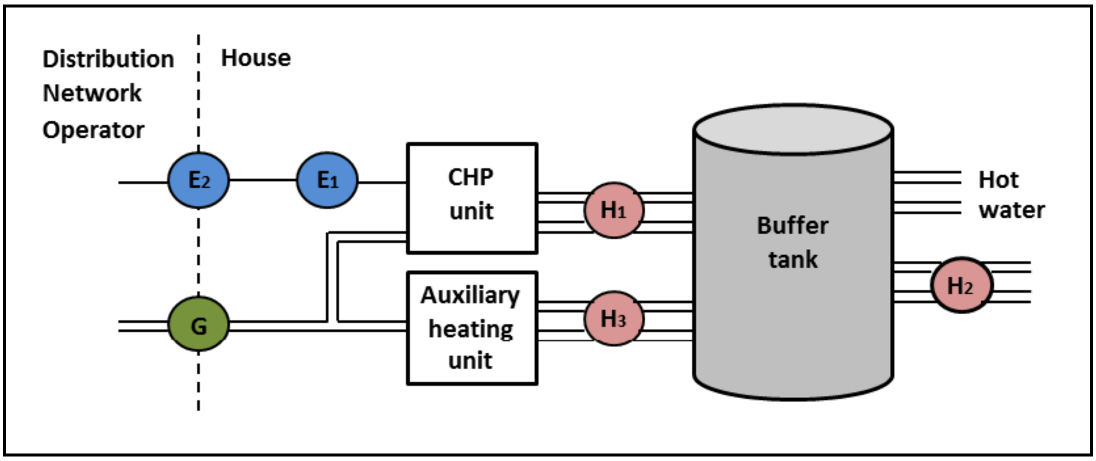

Figure 2: Arrangement of the basic components and the points of measurement for the Vaillant CHP systems. Cf. [2]

3.3. Characteristics and capacity of the buffer tanks

The buffer tank of the Brötje CHP system (SPS 800) has a volume of 774 liter. Similarly, the buffer tank size of the Vaillant CHP systems (VPS 800/3-7) is 778 liter. Both buffer tanks have a standing heat loss of 3.64 kWh/d at a temperature difference of 45 K between the buffer tank water and the air in the buffer tank room. Calculations of the buffer tank capacity are performed in section 4.5.

4. Economic feasibility of micro- and nano-CHP systems

In this section, the economic feasibility of micro- and nano-CHP systems are examined by means of a full cost accounting according to the economic and regulatory conditions in Germany in 2015. Furthermore, it is worked out from an economic point of view under which conditions the CH P unit should be operated and under which conditions the auxiliary heating unit should be operated in order to meet the heat demand of the building.

4.1. Reference heating system, economic and regulatory conditions

In this section, the economic feasibility of the micro- and nano-CHP systems taking part in the field test is evaluated in comparison to a conventional way of supplying heat and electricity to a residential building. The conventional reference heating system is defined as follows:

- state-of-the-art gas condensing boiler (η_{th} = 95%) for heat supply and
- electricity purchase from the local electricity provider.

The CHP bonus as well as the refund of energy tax are guaranteed for CHP operation, regardless of how the electricity is used. However, the economic value of the generated electricity and, thus, the profitability of the CHP system is heavily dependent on how the generated electricity is used (Tab. 3):

- electricity feed-in into the power grid: ca. 4 ct / kW_{el}
- electricity self-consumption (avoiding electricity purchase from the grid): ca. 26 ct / kW_{el}

These figures show the enormous economic advantage of electricity self-consumption and, indeed, the economic feasibility of nano- and micro-CHP-systems stands and falls with the rate of electricity self-consumption as shown in the following sections.

Economic and regulatory conditions concerning the application of micro-CHP systems in residential buildings in Germany (2015)

<table>
<tr><td>Cost of electricity</td><td>26.0</td><td>ct / kWh$_{el}$</td><td></td><td></td></tr>
<tr><td>Cost of natural gas</td><td>6.0</td><td>ct / kWh$_{gas}$</td><td></td><td></td></tr>
<tr><td>Refund of energy tax</td><td>0.55</td><td>ct / kWh$_{gas}$</td><td>for all kWh$_{gas}$ consumed by CHP unit</td><td>[10]</td></tr>
<tr><td>CHP bonus</td><td>5.41</td><td>ct / kWh$_{el}$</td><td>for all kWh$_{el}$ generated by CHP unit</td><td>[10]</td></tr>
<tr><td>Compensation for electricity feed-in *</td><td>3.21</td><td>ct / kWh$_{el}$</td><td rowspan="2">for all kWh$_{el}$ fed into grid</td><td>[11]</td></tr>
<tr><td>Compensation for avoided power network use **</td><td>0.8</td><td>ct / kWh$_{el}$</td><td>[12]</td></tr>
</table>

* average EEX baseload price (CHP index) in the first quarter 2015
** the actual value is established by the local network operator; common compensations are 0.4 – 1.5 ct / kWh [11]

Table 3: Economic and regulatory conditions concerning the application of micro-CHP systems in residential buildings in Germany (2015). [10] [11] [12]

4.2. Economic feasibility of the ecoPower 4.7 micro-CHP unit

4.2.1. Technical and energy parameters and maintenance cost of the ecoPower 4.7 CHP unit

The costs, revenues and savings per operating hour of the ecoPower 4.7 CHP unit as diagramed in Fig. 3 are calculated from the following technical parameters which are taken from the data sheet of the manufacturer [8]:

Technical and energy parameters of the ecoPower 4.7 micro-CHP unit

Net CHP electricity generation	4.65 kWh$_{el}$ / h
Heat generation of the CHP unit	12.5 kWh$_{th}$ / h
Overall efficiency of the CHP unit	90 %
Natural gas consumption	19.1 kWh$_{gas}$ / h

Table 4: Hourly electricity and heat generation and natural gas consumption. [8]

The thermal efficiency of auxiliary heating unit is assumed to be equal to the thermal efficiency of the reference heating system (95%). Hence, the heat generation of the auxiliary heating system does not have any influence on the profitability of the CHP system and does not need to be considered here.

The maintenance cost of the ecoPower 4.7 CHP unit is 40.5 cent per operating hour according to the full service contract offered by the Vaillant Group. [13] The full service contract includes a performance guarantee for the CHP unit which provides investment protection to the house owner. The contract is valid for a maximum of either 10 years or 59,999 operating hours; depending on which case occurs first. [13] Hence, the economic lifetime of the ecoPower 4.7 CHP unit is assumed as 60,000 hours in this paper.

4.2.2. Investment costs, investment subsidies and depreciation per operating hour

In addition to the BAFA and the progres.nrw subsidies, further subsidies for the purchase of a micro-CHP system can be obtained in some regions from the local electricity provider; a list can be found in [16]. However, as these additional subsidies by local electricity providers are not available to every house owner or investor, they are not considered in the calculations performed in this paper.

It also needs to be pointed out that the expenses for the installation of a micro-CHP system can differ considerably in different buildings according to the site-specific circumstances. The investment cost of the auxiliary heating unit is not included in Tab. 5 because it doesn't exceed the investment cost of the reference heating system and the CHP system replaces the reference heating system.

Additional investment costs of the ecoPower 4.7 micro-CHP system compared to a conventional heating system

Price of CHP unit	20,700 €	[14]
Price of buffer tank and accessories	1,500 €	[3]
Additional expenses for installation	1,800 €	[3]
BAFA* subsidy	2,870 €	[15]
progres.nrw** subsidy	2,345 €	[10]
Economic lifetime	60,000 hours	

* Bundesamt für Wirtschaft und Ausfuhrkontrolle (Federal Office of Economics and Export Control)
** Programm für Rationelle Energieverwendung, Regenerative Energien und Energiesparen; subsidy is obtainable until 31st Dec 2015

Table 5: Investment costs, investment subsidies and economic lifetime of ecoPower 4.7 CHP system.

The depreciation per operating hour as indicated in Fig. 3 (interspace between the dashed blue line and the dashed green line) does not include any financing costs like interests and is calculated linearly as follows:

$$\frac{\text{Price of CHP unit, buffer tank and accessories} + \text{Expenses for installation} - \text{BAFA subsidy} - \text{progres.nrw subsidy}}{\text{Economic lifetime}}$$

$$= \text{Depreciation per operating hour} = 31\ \text{ct/h}$$

4.2.3 Cash flow analysis

A cash flow analysis was performed for an hour of full load operation of the Vaillant ecoPower 4.7 CHP unit. The results are depicted in Fig. 3 as a function of the electricity self-consumption. Here, the dashed lines represent the hourly costs for operating the CHP unit and the continuous lines represent hourly revenues and savings. Please note that the costs as well as the revenues / savings are displayed as cumulative values.

The hourly saving for heat generation (78.9 ct/h) is lower than the hourly cost for the natural gas purchase (103.9 ct/h). The reason for this fact is that the thermal efficiency of the CHP unit (65.4%) is lower than the thermal efficiency of a state-of-the-art gas condensing boiler (approx. 95%). Interestingly, when the guaranteed CHP bonus of 5.41 ct / kWh_{el} is added to the savings for heat generation, then they match exactly the cost for the natural gas purchase (Fig. 3).

The profitability of operating a micro-CHP unit in a residential building is heavily dependent on the self-consumption rate of the generated electricity. For the ecoPower 4.7 CHP unit, the following values are determined (cf. Fig. 3 and Tab. 6):

- maximum saving per operating hour (100% electricity self-consumption): 49.3 ct / h
- minimum electricity self-consumption required to cover all costs: 51.8 %
- minimum electricity self-consumption required to cover operating costs: 21.2 %
  (natural gas purchase and maintenance cost)

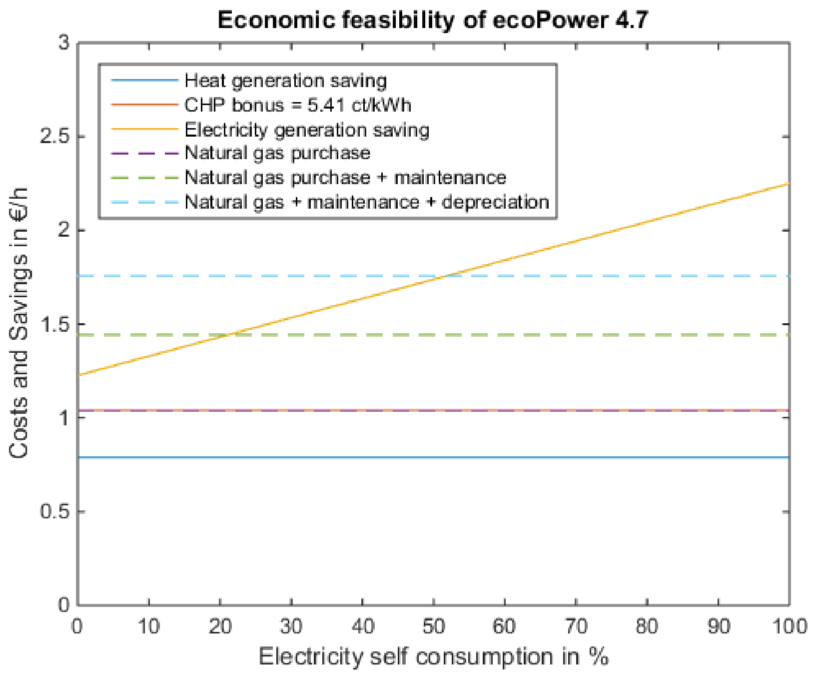

Figure 3: Cash flow analysis for an operating hour of the ecoPower 4.7 CHP unit.

4.2.4. Sensitivity analysis of depreciation variations

In order to evaluate the economic feasibility of micro-CHP systems in different building types and under varying economic conditions, the depreciation is a key parameter. The effective depreciation is determined by the investment and installation costs, the obtainable subsidies and the terms of financing.

Economic feasibility of the ecoPower 4.7 CHP system with respect to depreciation variations

	Minimum electricity self-consumption rate	**Corresponding minimum electricity demand**
CHP system as described above	51.8 %	2404 W
Depreciation + 20%	57.9 %	2692 W
Depreciation - 20%	45.6 %	2120 W
No depreciation (covering only natural gas purchase and maintenance cost)	21.2 %	986 W

Table 6: Economic feasibility of the ecoPower 4.7 CHP system with respect to changes of the depreciation per operation hour.

According to Tab. 6, the (average) electricity demand of the building within the operation period of the CHP unit must be at least 2404 W in order to realize an economic advantage compared to the reference heating system. Hence, as a rule of thumb, the ecoPower 4.7 CHP unit should be operated only when the electricity demand of the building reaches an average of 2500 W within the CHP operation period.

When the depreciation per operating hour of the ecoPower 4.7 CHP system changes by 20%, the minimum average electricity demand needed for a profitable operation of the CHP unit changes by almost 300 W.

4.2.5. Power modulation

The electricity generation of the ecoPower 4.7 CHP unit can be adjusted between 1.5 kW_{el} and 4.7 kW_{el} by regulating the engine speed. This raises the question whether the technical flexibility of the CHP unit can also be turned into an economical advantage for the operator of the micro-CHP system. For this reason, a second cash-flow analysis is carried out for operating the CHP unit in partial load at 3.0 kW_{el} and 8.0 kW_{th}, respectively – slightly above the critical electricity demand of approx. 2.5 kW as determined above for a profitable CHP operation in full-load mode. The following results are obtained:

- Maximum saving per operating hour (100% electricity self-consumption):	6.3 ct / h	
- Minimum electricity self-consumption required to cover all costs:	90.4 %	2712 W
- Minimum electricity self-consumption required to cover operating costs:	43.0 %	1290 W

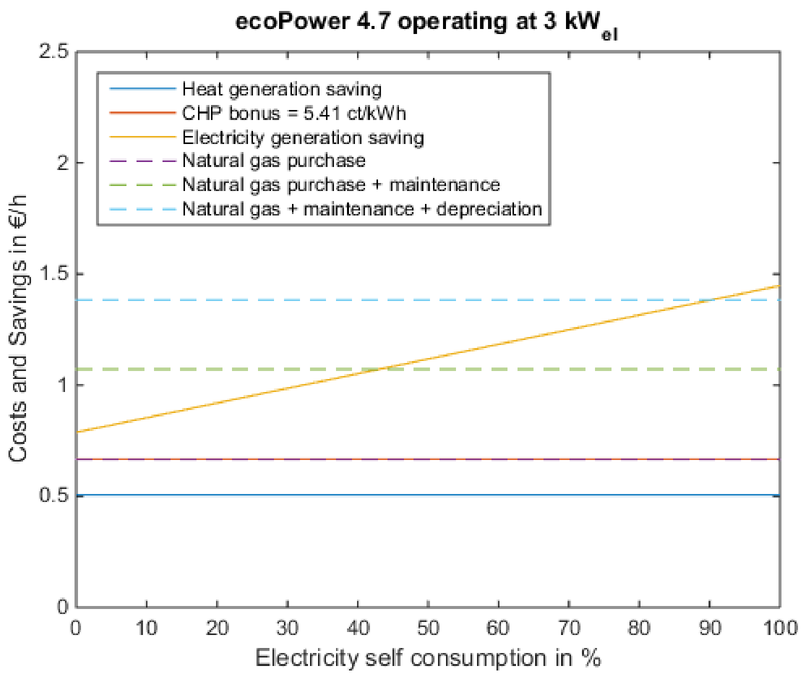

Figure 4: Cash flow analysis for an operating hour of the ecoPower 4.7 CHP unit operating in partial load at 3 kW_{el} and 8 kW_{th}, respectively.

The calculations show that the profitability of the ecoPower 4.7 CHP unit cannot be enhanced by down-regulating the electricity and heat generation: whereas in full-load mode a building electricity demand of 2404 W is mathematically sufficient in order to cover all costs for CHP operation (Tab. 6), this value rises to 2712 W when the CHP unit it operated in partial load at 3 kW_{el}.

The reason for this rather unexpected finding is that only one out of three elements of cost – the natural gas purchase – can be brought down by reducing the output of the CHP unit. The maintenance cost as well as the depreciation are fixed costs (per operating hour) and, thus, cannot be reduced whereas the revenues and savings for electricity and heat generation drop linearly with output reduction.

However, in practice additional factors – which are not considered in the calculations performed above – are relevant for the CHP system operator such as reduced wear and, thus, a potentially longer service life of the combustion engine when it is operated at lower speed levels. Also, the number of switching-on and switching-off procedures can be reduced by down-regulating the CHP power. Therefore, the arithmetically determined slight drop in profitability when the ecoPower 4.7 CHP unit is operated in partial load instead of full load might not be considered a technical and economical disadvantage by the CHP system operator.

Hence, the ecoPower 4.7 CHP system appears technically and economically appropriate for flexible electricity generation according to external requirements, for instance, in a virtual power plant. For example, the company *RWE Effizienz GmbH* offers a control unit called 'esayOptimize' which interconnects several micro-CHP systems to a virtual power plant. The interconnected micro-CHP systems participate in the balancing energy market via the RWE tertiary control pool where they can obtain additional revenues. [19]

4.3. Economic feasibility of nano-CHP units

4.3.1. ecoPower 1.0 nano-CHP unit (1kW$_{el}$ CHP unit with Otto engine)

Technical energy parameters of the ecoPower 1.0 nano-CHP unit

Net CHP electricity generation	0.96 kWh$_{el}$ / h
Heat generation of the CHP unit	2.50 kWh$_{th}$ / h
Overall efficiency of the CHP unit	92 %
Natural gas consumption	3.76 kWh$_{gas}$ / h

Table 7: Hourly electricity and heat generation and natural gas consumption. [8]

Investment costs, investment subsidies and economic lifetime of ecoPower 1.0 CHP system

Price of CHP unit, buffer tank, auxiliary heating system and accessories	14,680 €	[17]
Additional expenses for installation	1,500 €	[3]
Saved expenses for conventional heating system	- 3,000 €	[3]
BAFA subsidy	1,900 €	[15]
progres.nrw subsidy *	1,425 €	[10]
Economic lifetime	48,000 hours	[13]

* The progres.nrw subsidy is obtainable until 31st Dec 2015.

Table 8: Investment costs, investment subsidies and economic lifetime of ecoPower 1.0 CHP system.

Taking into account all the investment costs and subsidies listed in Tab. 8, an additional investment of 9,855 € results for the ecoPower 1.0 CHP system compared to the reference heating system. The economic lifetime as guaranteed by the full service contract of the Vaillant Group is 48,000 operating hours (20% less than for ecoPower 4.7) or 10 years. [13] This results in a depreciation of 20.5 cent per operating hour (approx. 2/3 of the depreciation of the ecoPower 4.7 CHP unit).

Cash flow analysis for the ecoPower 1.0 nano-CHP unit shows that the savings for heat generation plus the CHP bonus slightly overmatch the costs for the natural gas purchase (Fig. 5). When the rate of electricity self-consumption exceeds 49.1 % – corresponding to a building electricity consumption of 471 W – the maintenance cost is compensated by the economic value of the generated electricity (savings of electricity purchase from the grid + revenues for electricity feed-in and avoided power network use; cf. Tab. 3).

Therefore, the ecoPower 1.0 nano-CHP unit must not be operated in time periods with an (average) electricity consumption of the building below 471 W in order to avoid sustaining a financial loss. If the generated electricity replaces the same amount of electricity purchase from the grid (100% self-consumption), the ecoPower 1.0 CHP unit can gain 10.75 cent per operating hour in order to pay off part of the investment cost.

Hence, theoretically, if the ecoPower 1.0 CHP unit would never feed any electricity into the grid, it could gain a maximum amount of 0.1075 € / h * 48,000 h = 5,160 € for paying off part of the investment cost. This amount is about 52% of the effective investment cost of 9,855 € (subsidies already taken into account).

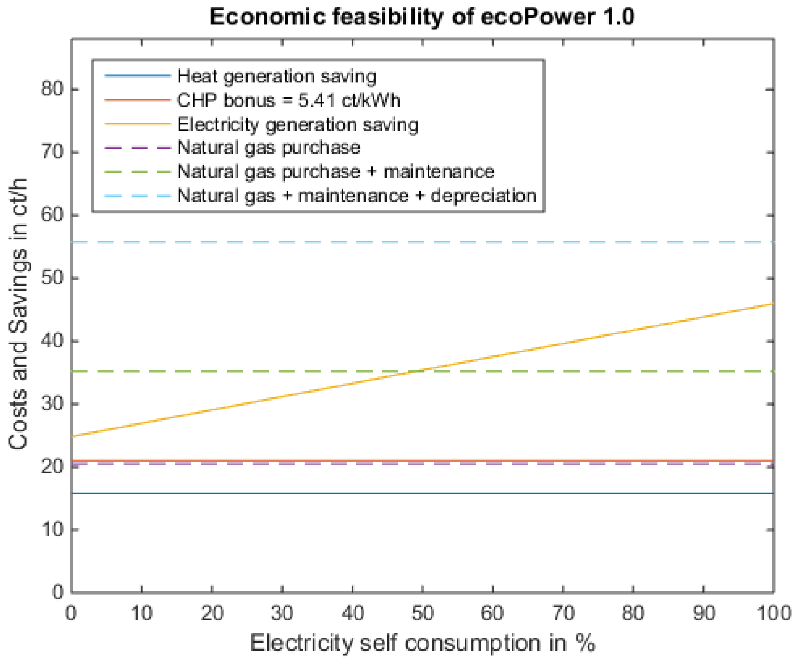

Figure 5: Cash flow analysis for an operating hour of the ecoPower 1.0 CHP unit.

Although the ecoPower 1.0 nano-CHP system is evaluated as 'economically not feasible', two important factors need to be considered with respect to the *CHP pilot project for CO_2 reduction in the InnovationCity Bottrop*:

1. the intangible value of the fact, that electricity and heat is generated within the 'own four walls', providing certain energy autonomy to the house owner and
2. that the participants of the CHP pilot project could purchase their nano-CHP system at a price similar to the price of a conventional state-of-the art heating system such as the reference system described in section 4.1

4.3.2. 1kW$_{el}$ nano-CHP systems with Stirling engine

The evaluation of the economic feasibility of 1 kW$_{el}$ nano-CHP systems with Stirling engine described in this subsection refers to the following CHP systems which participate in the field test in Bottrop:

- Brötje EcoGen WGS 20.1
- Viessmann Vitotwin 300W

Technical energy parameters of the 1kW$_{el}$ Stirling nano-CHP unit

Net CHP electricity generation	0.96 kWh$_{el}$ / h
Heat generation of the CHP unit	5.60 kWh$_{th}$ / h
Overall efficiency of the CHP unit	92 %
Natural gas consumption	7.13 kWh$_{gas}$ / h

Table 9: Hourly electricity and heat generation and natural gas consumption.

Investment costs, investment subsidies and economic lifetime of 1kW$_{el}$ Stirling CHP system

Price of CHP unit (includes gas condensing boiler for peak loads)	13,000 €	[3]
Price of buffer tank and accessories	1,500 €	[3]
Additional expenses for installation	1,500 €	[3]
Saved expenses for conventional heating system	- 3,000 €	[3]
BAFA subsidy	1,900 €	[15]
progres.nrw subsidy *	1,425 €	[10]
Economic lifetime	50,000 hours	

* The progres.nrw subsidy is obtainable until 31st Dec 2015.

Table 10: Investment costs, investment subsidies and economic lifetime of a 1kW$_{el}$ Stirling CHP system.

According to Tab. 10, the additional investment for a 1 kW$_{el}$ Stirling CHP system compared to the reference heating system is 9675 € and, thus, very similar to the ecoPower 1.0 CHP system. The economic lifetime is assumed as 50,000 operating hours. The resulting depreciation of 19.4 cent per operating hour is about 1 ct / h less than for the ecoPower 1.0 CHP system.

The analysis of the economic feasibility of the 1 kW Stirling CHP systems is rather complicated due to the following reasons:

- Uncertain **maintenance cost** per operating hour:
  - The full service contract offered by the Brötje Group includes the annual payment of a fixed amount of 390 € / year. Hence, the maintenance cost per operating hour is highly dependent on the annual number of operation hours of the CHP unit.
  - In contrast, the Viessmann Group does not offer a full service contract for its Vitotwin 300W nano-CHP system and leaves the design of the contract terms for maintenance to the installer of the CHP system. In this paper, the conditions of the full service contract of the Brötje Group are also applied to the Viessmann nano-CHP systems.
- Possibly, the low-maintenance Stirling engine lasts for a longer period of time than the 50,000 operating hours assumed in Tab. 10.
- The electricity and heat output of the nano-CHP system is modulated when the head temperature of the Stirling engine is changed. This power modulation – although initiated automatically by the control unit of the Stirling engine and, thus, not influenceable by the operator of the CHP system – in general is favourable for the CHP operator since electricity and heat output are down-regulated, yielding higher self-consumption of the generated electricity.

Because of these uncertainties, the cash-flow analysis for the 1 kW Stirling CHP systems (Fig. 6) is performed with two different assumptions for the operating hours of the CHP unit per year:

Annual operating hours of CHP unit	Maintenance cost per operating hour	Minimum electricity self-consumption rate *	Corresponding minimum building electricity consumption
3500 h/a	11.1 ct / h	26.5%	254 W
2000 h/a	19.5 ct / h	66.1%	635 W

* in order to cover the expenses for natural gas purchase and maintenance

The numerical values stated for the minimum electricity self-consumption and building electricity consumption, respectively, need to be regarded with caution because they are highly sensitive to the precise terms of contract which are offered by the manufacturer or by the installer of the CHP system.

According to the analyses performed in this section, it is very unlikely that by the operation of a 1 kW Stirling nano-CHP system in a residential home all costs including depreciation can be covered by the savings for heat and electricity generated by the alternative heating system. At 100% electricity self-consumption, the following costs and savings are determined per operating hour (cf. Fig. 6):

Costs:	38,9 ct / h	natural gas purchase	**Savings:**	35.4 ct / h	heat
	19.4 ct / h	depreciation		5.2 ct / h	CHP bonus
	11.1 ct / h	*maintenance (3500 h/a)*		25.0 ct / h	electricity
	69.4 ct / h			**65.6 ct / h**	

Consequently, if the maintenance cost would drop – due to a revised full service contract and / or a very high number of operating hours per year – by at least 3.9 ct / h down to 7.2 ct / h or lower, the 1 kW Stirling nano-CHP system was operated in a ‘profitable’ way, i.e. the savings for alternative heat and electricity generation cover the costs of the CHP system (depreciation is calculated without any interest payments for the capital expenditure).

The 1 kW nano-CHP unit with Stirling engine is the only CHP unit evaluated in this paper whose savings for heat generation plus CHP bonus exceed considerably the cost for the natural gas purchase (see above, Fig. 6) due to its high thermal efficiency.

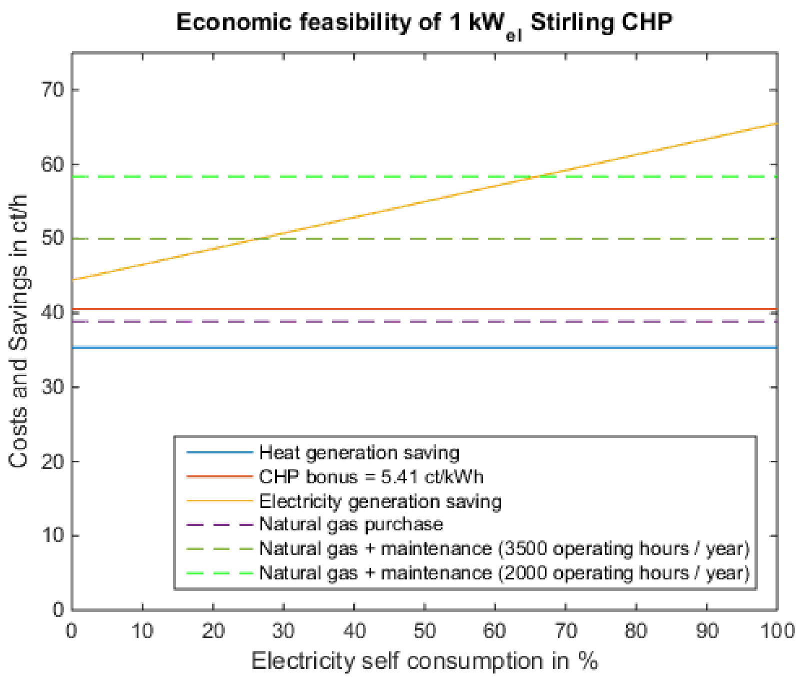

Figure 6: Cash flow analysis for an operating hour of the 1 kW$_{el}$ Stirling CHP units.

5. Analysis of the current heat-led operation of the CHP systems

5.1. Electricity self-consumption

According to the analyses of the previous section, the most important parameter for the economic feasibility of micro- and nano-CHP systems installed in residential buildings is the rate of self-consumption of the generated electricity. For the buildings with nano-CHP systems evaluated in this paper, the average monthly electricity self-consumption is listed in Tab. 11. For the multi-family home (MFH), the respective values are not available since there is no central meter that measures the electricity consumption of the entire building (every apartment has its own electricity meter).

Electricity self-consumption as measured in the field test (heat-led CHP operation)

Month	TH1	TH2	TH3	TH4	SFH
Dec	78,5%	65,7%	47,8%	36,2%	37,1%
Jan	67,9%	64,5%	44,3%	33,8%	29,7%
Feb	65,5%	61,0%	42,2%	28,8%	28,4%
Mar	67,1%	64,0%	44,0%	28,8%	21,9%
Apr	73,4%	60,9%	34,6%	28,8%	25,5%
May	87,3%	67,5%	35,4%	26,8%	26,0%
Jun	87,0%	65,8%	40,7%	28,1%	25,6%

Tab 11: Electricity self-consumption as measured in the field test in Bottrop (heat-led CHP operation).

The highest self-consumption rates are found in TH1 with monthly averages between 65.5% in February and 87.3% in May. In this building, the rates are lowest from January to March and increase towards the summer. TH2 is the second building in which more than 50% of the generated electricity are consumed on-site by the residents. The monthly rates in TH2 vary between 60.9% and 67.5% and do not show significant changes between the seasons (Tab. 11).

In TH3, TH4 and SFH electricity self-consumption is considerably less than 50% in all months within the investigation period. In each of these buildings, December is the month with highest self-consumption – probably because of increased illumination in the darkest month of the year as well as additional light decoration and domestic activities due to Advent and Christmas.

In TH3, electricity self-consumption drops from about 48% in December to about 35% in April and May. In TH4, self-consumption declines from about 36% in December and 34% in January to 27% – 29% in the months from February to June. According to the analyses performed in the previous section 4.3.2, these levels of electricity self-consumption are hardly sufficient in order to operate the Stirling CHP systems installed in TH3 and TH4 in such way, that the costs for natural gas purchase and maintenance are compensated by the savings for alternative heat and electricity supply. For this reason, there is large need for energy management that aims at an increasing electricity self-consumption.

In SFH, apart from December (37%) all months have self-consumption rates below 30% and drop as low as 22% (in March) which is the lowest monthly average value of all buildings evaluated in this paper (Tab. 11). The structural differences between the electricity demand and the electricity generation profiles in a building with low (SFH) and high (TH2) electricity self-consumption rate can be distinguished in Fig. 7 and Fig. 8, respectively. According to the cash-flow analysis in chapter 4.3.1, the electricity self-consumption is not sufficient for the ecoPower 1.0 nano-CHP system installed in SFH in order to cover the expenses for natural gas purchase and maintenance.

5.2. Heat and electricity generation by CHP systems and comparison to the building demand

The average electricity self-consumption described in the previous subsection results from the ratio of the building's electricity demand (in the times of CHP operation) and the electric power of the CHP unit. Besides electricity self-consumption, there is another important parameter that determines the economic feasibility of a micro-/nano-CHP system in residential buildings: the ratio of the heat / electricity consumption in the building.

This ratio of the **heat / electricity demand** varies considerably among the buildings under evaluation and, of course, also changes completely between summer and winter as listed in Tab. 12. In winter, the heat / electricity demand reaches from less than 5 in TH1 and TH2 up to 14 in TH4 and 16 in SFH. By the month of June, this ratio has dropped down to 3.1 in TH4, 2.6 in SFH and 1.6 in TH2. TH1 is the only building whose electricity demand in summer exceeds the summerly heat demand (the heat / electricity ratio in May and June is 0.7 and 0.5, respectively).

On the other hand, the ratio of the **heat / electricity generation** by the CHP system is almost constant in the course of the year in TH1 and TH4 at a value around 6. This value is close to the ratio of the nominal powers (P_{th} / P_{el}) of the respective Stirling CHP units (*EcoGen WGS 20.1* and *Vitotwin 300W*) and indicates that the auxiliary heating unit did not contribute substantially to the heat supply of the building – not even in winter. In TH2, the same Stirling CHP system operates at a considerably larger heat / electricity generation ratio which drops from 11.3 in March to 8.3 in June. Apparently, the auxiliary heating unit has run and supplied heat to the buffer tank, even in the month of June.

In the multi-family home (MFH), the CHP heat / electricity generation ratio is by far the lowest within the winter period (at a value of 3.9) and also in March (3.6). The reason is the high electrical efficiency of the 4.7 kW_{el} Otto engine (in comparison to the Stirling engines; see Tab. 2) and, respectively, the comparatively low contribution of the auxiliary heating unit in heat generation (in comparison to SFH; see Tab. 14). In April and May a considerably larger heat / electricity generation ratio is detected because in these months the CHP unit was out of operation for considerable time periods as further discussed in section 5.3.

Overview over the heat and electricity generation (CHP system) and consumption (building)

Building	Month	Total heat consumption = Total heat generation	Electricity consumption of building	Electricity generation (CHP)	Electricity feed-in into grid	Heat / Electricity consumption (building)	Heat / Electricity generation by CHP system	Self consumption of generated electricity	Self consumption / Electricity consumption of building
		H_1	E	E_1	E_2				
		[kWh]	[kWh]	[kWh]	[kWh]	= H_1 / E	= H_1 / E_1	= (E_1 - E_2) / E_1	= (E_1 - E_2) / E
TH1	Ø Dec - Feb	2443	516	411	120	4,7	5,9	70,9%	56,4%
	Mar	1591	505	261	86	3,2	6,1	67,1%	34,7%
	Apr	873	566	137	37	1,5	6,4	73,4%	17,8%
	May	477	681	73	9,3	0,7	6,5	87,3%	9,4%
	Jun	316	631	50	6,5	0,5	6,3	87,0%	6,9%
TH2	Ø Dec - Feb	2187	480	205	74	4,6	10,7	63,7%	27,2%
	Mar	2139	477	189	68	4,5	11,3	64,0%	25,4%
	Apr	1480	441	148	58	3,4	10,0	60,9%	20,5%
	May	1123	461	127	41	2,4	8,8	67,5%	18,6%
	Jun	772	469	93	32	1,6	8,3	65,8%	13,0%
TH3	Ø Dec - Feb	-	319	355	196	-	-	44,8%	49,7%
	Mar	-	327	312	175	-	-	44,0%	42,0%
	Apr	-	257	172	112	-	-	34,6%	23,1%
	May	-	312	88	57	-	-	35,4%	10,0%
	Jun	-	304	38	23	-	-	40,7%	5,1%
TH4	Ø Dec - Feb	3057	217	484	324	14,1	6,3	33,0%	73,7%
	Mar	2484	202	438	312	12,3	5,7	28,8%	62,4%
	Apr	1511	186	268	191	8,1	5,6	28,8%	41,5%
	May	887	166	158	116	5,3	5,6	26,8%	25,5%
	Jun	449	144	82	59	3,1	5,5	28,1%	15,9%
SFH	Ø Dec - Feb	4480	275	613	418	16,3	7,3	31,8%	70,9%
	Mar	3244	204	517	404	15,9	6,3	21,9%	55,5%
	Apr	2012	221	249	186	9,1	8,1	25,5%	28,7%
	May	1079	219	334	247	4,9	3,2	26,0%	39,6%
	Jun	536	204	214	159	2,6	2,5	25,6%	26,9%
MFH	Ø Dec - Feb	8843	-	2239	-	-	3,9	-	-
	Mar	7543	-	2091	-	-	3,6	-	-
	Apr	4836	-	889	-	-	5,4	-	-
	May	3548	-	443	-	-	8,0	-	-
	Jun	3126	-	860	-	-	3,6	-	-

Table 12: Overview over heat and electricity consumption of the buildings under evaluation as well as heat and electricity generation by the CHP systems.

In SFH, the heat / electricity generation ratio drops from 7.3 in the winter months to 2.5 in June. The latter value corresponds to the ratio of the nominal powers of the ecoPower 1.0 CHP unit (2.5 kW_{th} / 1.0 kW_{el} = 2.5). Hence, June is supposed to be the first month in the year 2015 in which the auxiliary heating unit did not contribute substantially to the heat supply of the building. A closer analysis, based on the second heat meter installed in buildings with ecoPower CHP systems (Fig. 2), however shows that about 10% of the heat demand in June in SFH was supplied by the auxiliary heating unit (Tab. 14).

According to Tab. 12, SFH is the only building in which the amount of electricity generated by the CHP unit exceeds the electricity consumption of the building in every month within the investigation period. The reasons for this finding are the high electrical efficiency of the ecoPower 1.0 CHP system as well as its small thermal efficiency which allows for considerable operation hours of the CHP system even in the summer months with little heat demand.

However, electricity generation and consumption do not match well in SFH; the mismatch is displayed at the example of a summer day in Fig. 7. In June, for instance – although the amount of electricity generation (214 kWh) and electricity consumption (204 kWh) is similar to each other – only 25.6% of the generated electricity was consumed on-site in SFH. On the other side, only 26.9% of the building's electricity demand was supplied by the CHP unit (Tab. 12). Hence, there is large potential for energy management especially in summer in order to increase electricity self-consumption and, thus, the profitability of the CHP system. Within the winter period, more than 70% of the building's electricity demand was supplied by the CHP at a self-consumption rate of about 32% (Tab. 12).

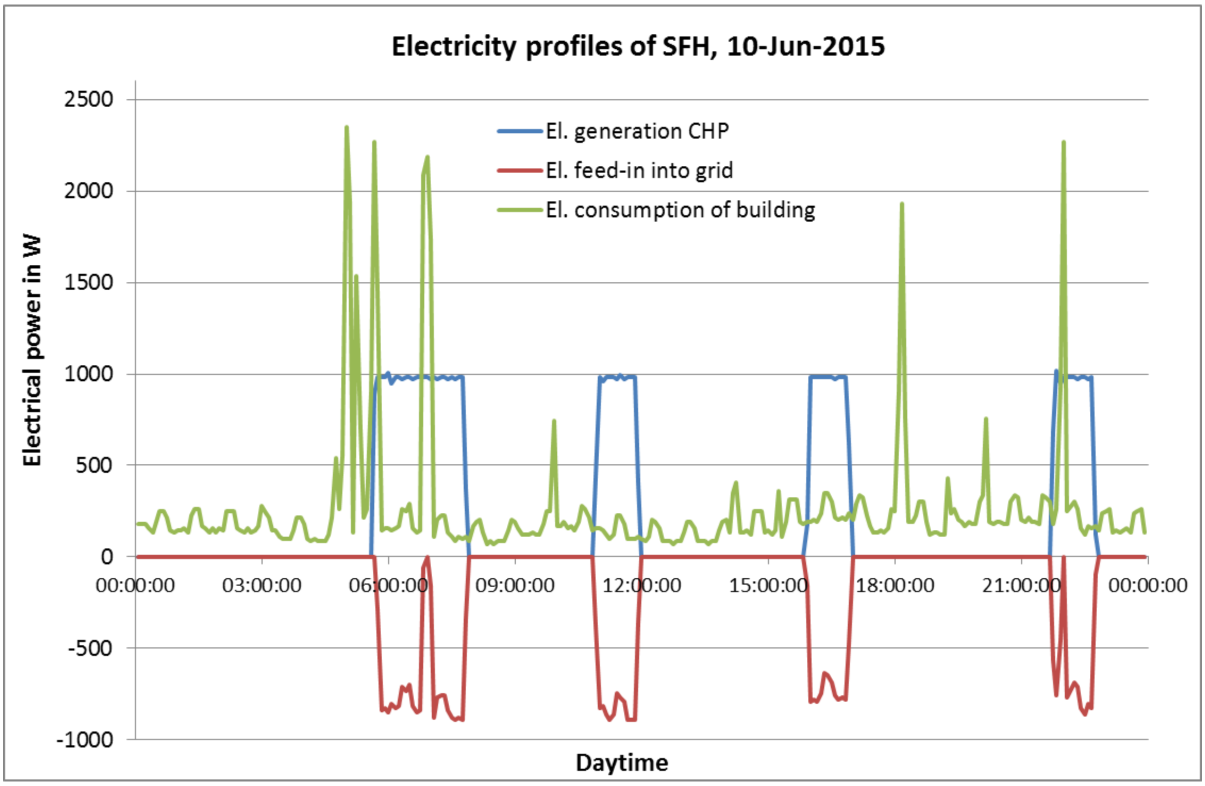

Figure 7: Electricity profiles of the CHP generation, the feed-in into the grid and the building consumption in SFH on 10th Jun 2015.

In TH4, almost 74% of the building's electricity demand within the winter period was supplied by the CHP unit – the highest value of all buildings under evaluation (Tab. 12). Towards summer, this percentage decreases along with the heat demand down to 16% in June. Thus, June is in all buildings the month with the lowest share of CHP-generated electricity at the building's electricity demand, dropping as low as 5% in TH3 and 7% in TH1. Within the winter period, the Stirling CHP system in these buildings accounted for 50% (TH3) and 56% (TH1) of the respective electricity consumption.

In TH2, only 27% of the building's electricity demand between December and February was covered by the Stirling CHP system – by far the lowest value within the winter period of all buildings. However, towards summer this share decreases less than in any other building and still reaches a value of 13% in June (Tab. 12). These differences compared to the other buildings can be explained by analyzing the electricity profiles in TH2. Fig. 8 shows exemplary profiles of the CHP generation, the feed-in into the grid and the building consumption on a comparatively cold winter day.

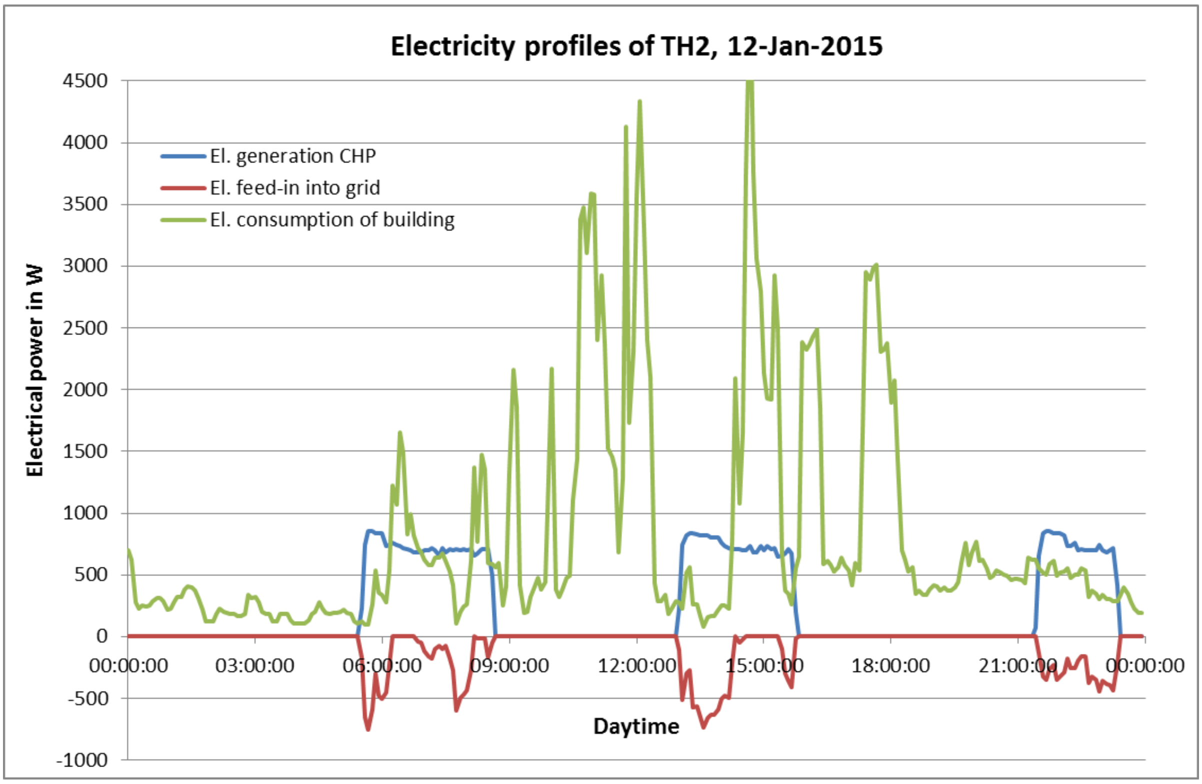

Figure 8: Electricity profiles of the CHP generation, the feed-in into the grid and the building consumption in TH2 on 11th Jan 2015.

On 11th Jan 2015 – a fairly representative day of the winter period – the overall operating time of the CHP unit was rather short; and a substantial share of the building's heat demand was supplied by the auxiliary heating unit (not visible in Fig. 8). Moreover, the Stirling engine was operating at a reduced electric power of approx. 700 W which causes the very low contribution of the CHP unit to the building's electricity demand. On the other hand, the low electric power of the Stirling engine (which is detected for most days in TH2) leads to the particularly high electricity self-consumption rates compared to other buildings (Tab. 12) – even higher self-consumption is only found in TH1 which has a considerably higher monthly electricity consumption than TH2.

According to the electricity profiles displayed in Fig. 8, there is large potential for on-site energy management and CHP profitability enhancement in TH2, especially by shifting parts of the high electricity consumption into the operating times of the nano-CHP unit.

5.3. Electrical and thermal efficiency of the CHP systems

The **electrical and thermal system efficiency** described in this section are calculated as the ratio E_1 / G and H_1 / G, respectively, as specified in Tab. 13. Hence, these efficiency values characterize the *electrical and thermal efficiency of the entire CHP system* (as installed and operated) with respect to the higher heating value (HHV) of the natural gas. They must not be mistaken for engine efficiencies nor for energy efficiencies with respect to the lower heating value (LHV).

The **overall efficiency** (electrical + thermal system efficiency) is almost constant between December and May in the buildings with Stirling CHP system and ranges from about 78.5% in TH2 to about 83.5% in TH1 and approx. 85.5% in TH4. [Tab. 13] This is considerably lower than the value of 92% which is used in section 4.3.2 for the analysis of the economic feasibility of 1 kW_{el} Stirling nano-CHP systems. In June, the overall efficiency is between 1.5% and 2.5% lower than in the months up to May.

The ecoPower 1.0 nano-CHP system with Otto engine in SFH reaches overall efficiencies just under 82% between December and April. This is 10% below the value of 92% as specified in the data sheet of the manufacturer [8] and as used in the profitability analysis in section 4.3.1. In May and June the overall efficiency drops to about 74.5%. [Tab. 13] The overall efficiency of the ecoPower 4.7 micro-CHP system – reaching approx. 80% between December and May (76.4% in June) – is also 10% below the value of 90% as specified in the data sheet [8] and used for the profitability analysis in section 4.2.

Overview over energy consumption, electricity generation and system efficiencies

		G	H_1	E	E_1	E_2			
Building	**Month**	**Natural gas consumption (HHV)**	**Total heat consumption = Total heat generation**	**Electricity consumption of building**	**Electricity generation (CHP)**	**Electricity feed-in into grid**	**Thermal system efficiency**	**Electrical system efficiency**	**Overall system efficiency**
		[kWh]	[kWh]	[kWh]	[kWh]	[kWh]	$= H_1 / G$	$= E_1 / G$	$= (H_1+E_1) / G$
TH1	Ø Dec - Feb	3441	2443	516	411	120	71,0%	11,9%	82,9%
	Mar	2198	1591	505	261	86	72,4%	11,9%	84,3%
	Apr	1192	873	566	137	37	73,2%	11,5%	84,7%
	May	667	477	681	73	9,3	71,5%	11,0%	82,5%
	Jun	450	316	631	50	6,5	70,2%	11,1%	81,3%
TH2	Ø Dec - Feb	3076	2187	480	205	74	71,1%	6,7%	77,8%
	Mar	2914	2139	477	189	68	73,4%	6,5%	79,9%
	Apr	2075	1480	441	148	58	71,3%	7,1%	78,5%
	May	1600	1123	461	127	41	70,2%	7,9%	78,1%
	Jun	1116	772	469	93	32	69,2%	8,3%	77,5%
TH3	Ø Dec - Feb	4182	-	319	355	196	-	8,5%	-
	Mar	3481	-	327	312	175	-	9,0%	-
	Apr	1857	-	257	172	112	-	9,2%	-
	May	918	-	312	88	57	-	9,6%	-
	Jun	406	-	304	38	23	-	9,4%	-
TH4	Ø Dec - Feb	4113	3057	217	484	324	74,3%	11,8%	86,1%
	Mar	3419	2484	202	438	312	72,6%	12,8%	85,4%
	Apr	2081	1511	186	268	191	72,6%	12,9%	85,5%
	May	1233	887	166	158	116	72,0%	12,8%	84,8%
	Jun	641	449	144	82	59	70,1%	12,8%	82,9%
SFH	Ø Dec - Feb	6242	4480	275	613	418	71,8%	9,8%	81,6%
	Mar	4589	3244	204	517	404	70,7%	11,3%	82,0%
	Apr	2767	2012	221	249	186	72,7%	9,0%	81,7%
	May	1865	1079	219	334	247	57,9%	17,9%	75,7%
	Jun	1023	536	204	214	159	52,4%	20,9%	73,3%
MFH	Ø Dec - Feb	13866	8843	-	2239	-	63,8%	16,1%	79,9%
	Dec	13792	8173	-	2636	-	59,3%	19,1%	78,4%
	Jan	14118	9759	-	1739	-	69,1%	12,3%	81,4%
	Feb	13689	8597	-	2342	-	62,8%	17,1%	79,9%
	Mar	12166	7543	-	2091	-	62,0%	17,2%	79,2%
	Apr	7152	4836	-	889	-	67,6%	12,4%	80,0%
	May	4990	3548	-	443	-	71,1%	8,9%	80,0%
	Jun	5217	3126	-	860	-	59,9%	16,5%	76,4%

Table 13: Overview over the energy consumption (natural gas, heat and electricity), the generation and feed-in of electricity as well as the system efficiencies (thermal, electrical, overall).

Regarding the **electrical system efficiency**, the highest monthly values of all buildings are reached in SFH at 21% in June and 18% in May, respectively. The reason is that the Otto engine of the ecoPower 1.0 CHP unit in SFH has a considerably higher electrical engine efficiency (26.3%) than the Stirling engine (about 17%) as listed in Tab. 2. Moreover, in summer the auxiliary heating unit should not operate and, thus, not contribute to the gas consumption either. *(Nevertheless, a small quantity of heat must have been generated by the auxiliary heating unit in SFH according to Tab. 14.)* In winter, the electrical system efficiency in SFH reaches only about 10% due to the substantial heat generation (and gas consumption) by the auxiliary heating unit (Tab. 14).

In MFH, the monthly electrical system efficiency of the ecoPower 4.7 CHP system reached up to 19% in March and 17% in February and March. Due to the high electrical efficiency of the Otto engine of 24.6%, it is technically feasible to reach higher electrical system efficiencies than the recorded values in Tab. 13. The reason for not reaching higher electrical system efficiencies is that in every month of the investigation period the auxiliary heating unit contributes more than 20% to the heat generation in MFH as listed in Tab. 14. In January, April and May the electrical efficiency of the ecoPower 4.7 CHP system was particularly low since the CHP unit was out of operation for considerable time periods in these months. This conclusion can be drawn from the measurement values listed in Tab. 13 and 14:

- The electricity and heat generation by the CHP unit was much lower in these months than in the adjacent months and also
- the percentage of the CHP unit's heat generation at the total heat generation is much lower.

Breakdown of heat generation and consumption in the buildings with ecoPower CHP system

		$H_1 + H_3$	H_1	H_3	H_2	HW	E_1			
Building	Month	Total heat generation	Heat generation: CHP unit	Heat generation: Auxiliary heating unit	Demand for space heating	Hot water generation and buffer tank losses	Electricity generation (CHP)	CHP heat generation / Total heat generation	Percentage of heat generation by auxiliary heating unit	CHP heat generation / CHP electricity generation
		$= H_1 + H_3$	[kWh]	[kWh]	[kWh]	$H_1 + H_3 - H_2$	[kWh]	$= H_1/(H_1+H_3)$	$= H_3/(H_1+H_3)$	$= H_1/E_1$
SFH	Ø Dec - Feb	4480	1479	3001	-	-	613	33,0%	67,0%	2,41
	Mar	3244	1250	1994	-	-	517	38,5%	61,5%	2,42
	Apr	2012	597	1415	-	-	249	29,7%	70,3%	2,40
	May	1079	778	301	-	-	334	72,1%	27,9%	2,33
	June	536	483	53	-	-	214	90,1%	9,9%	2,25
MFH	Ø Dec - Feb	8843	6252	2591	7787	1056	2239	70,7%	29,3%	2,79
	Dec	8173	7277	896	7091	1082	2636	89,0%	11,0%	2,76
	Jan	9759	4875	4884	8656	1103	1739	50,0%	50,0%	2,80
	Feb	8597	6605	1992	7613	984	2342	76,8%	23,2%	2,82
	Mar	7543	5913	1630	6458	1085	2091	78,4%	21,6%	2,83
	Apr	4836	2511	2325	3889	947	889	51,9%	48,1%	2,82
	May	3548	1218	2330	2643	905	443	34,3%	65,7%	2,75
	June	3126	2361	765	2174	952	860	75,5%	24,5%	2,75

Table 14: Breakdown of heat generation and consumption within the winter period in the buildings with ecoPower CHP system (SFH and MFH).

The highest electrical system efficiencies of the Stirling nano-CHP systems are recorded in TH1 and TH4. In both buildings, the monthly values are fairly constant in the course of the year and reach between 11% and 12% in TH1 and almost 13% (during winter: just under 12%) in TH4, respectively (Tab. 13). The lowest monthly electrical system efficiencies are detected in TH2 at values between 6.5% in March (and January) and 8.3% in June. There are two reasons for the low electrical system efficiency in TH2:

- The Stirling engine often lowers its electric power to approx. 700 W in TH2 and
- the operating periods of the CHP unit in TH2 are shorter than in the other buildings with Stirling nano-CHP system because of long operating periods of the auxiliary heating unit.

5.4 Heat generation by the CHP unit and the auxiliary heating unit in the course of the year

A more detailed examination of the heat generation is possible for the ecoPower CHP systems installed in SFH and MFH since they have separate heat meters for the CHP unit and the auxiliary heating unit, respectively, as depicted in Fig. 2.

In SFH, the contribution of the ecoPower 1.0 CHP unit to the total heat generation ranges from 33% in the winter months to 90% in June (Tab. 14). The CHP unit was operated nonstop (24 h/d) on many days within the winter period due to its small thermal power and the large heat demand of the building (classical heat-led operation). A simple consideration shows the following:

- The CHP unit has a thermal power of 2.5 kW_{th} and, thus, can generate maximum diurnal heat quantity of 2.5 kW * 24 h/d = 60 kWh/d.

- On the other hand, in SFH the average daily heat consumption within the winter period was 4480 kWh / 30 d = 149.3 kWh/d.

The ratio of heat / electricity generation of the ecoPower 1.0 CHP unit was determined as about 2.41 between December and April, which is slightly less than the ratio of the nominal powers (2.5 kW_{th} / 1.0 kW_{el} = 2.5). Towards the summer months, the ratio drops to 2.33 in May and 2.25 in June (Tab. 14).

In the multi-family home, between 70% and 80% of the heat was generated by the ecoPower 4.7 CHP unit in the months from December to March and also in June (Tab. 14). In April and May, only 52% and 34%, respectively, of the heat demand were generated by the CHP unit (probably due to non-availability of the CHP unit). The heat / electricity generation ratio of the CHP unit was approx. 2.8 (in May and June slightly lower than in the colder months). This is higher than the ratio of the nominal powers (12.5 kW_{th} / 4.7 kW_{el} = 2.67) and also higher than the respective ratio of the ecoPower 1.0 CHP unit.

5.5. Buffer tank capacity and management

The buffer tank is a fundamental component of every CHP system. In the classic heat-led operation, its main function is to reduce the number of startings of the engine in order to extend the service life of the engine and the entire CHP system.

Besides that, the heat capacity of the buffer tank water can be used for purposeful buffer tank management. For example, heat might be purposefully stored for a posterior time of day with a higher heat demand so that the auxiliary heating unit is not (or to a lesser extend) required in these hours of particularly high heat demand. In doing so, the operation duration of the auxiliary heating unit can be minimized and the operation duration of the CHP unit can be maximized in order to increase electricity generation at a given heat demand.

In general, buffer tank management enables a certain degree of flexibility for the CHP operation by partly decoupling plant operation (i.e. heat generation) from the current heat demand of the building. The heat quantity ΔQ which can be stored in a buffer tank can be calculated according to

$$\Delta Q = c_p \cdot \rho \cdot V \cdot \Delta T$$

$$c_p \approx 4.18\ kJ/(kg \cdot K)\ ,\ \rho \approx 0.99\ kg/l$$

The calculations in Tab. 15 are performed with an active buffer tank volume V of 750 liter which is slightly less than the nominal buffer tank volumes of about 775 liters (cf. section 3.3). Tab. 15 shows by how much the temperature of the buffer tank water increases when a certain quantity ΔQ is stored in the tank. For each heat quantity also the duration is given that a CHP unit with certain thermal power operates in order to generate that heat quantity. This operation duration is the flexibility gained for the operation of the CHP unit.

Buffer tank capacity

According to the manufacturer, the standing heat loss of the buffer tank according to DIN EN 12897 is 3.64 kWh/d at a temperature difference of 45 K between the buffer tank water and the air in the buffer tank room. Hence, the continuous heat output is 150 W under these conditions and sums up to approximately 110 kWh per month. Since it depends linearly on the temperature difference, an increased temperature level in the buffer tank due to buffer tank management causes an additional heat outlet into the buffer tank room.

Heat quantity ΔQ	Temperature increase ΔT	Operation duration [h] of a CHP unit with a thermal power of				
[kWh]	[K]	2,5 kW	5,7 kW	6,7 kW	9,5 kW	12,5 kW
6	6,9	2,4	1,1	0,9	0,6	0,5
12	13,8	4,8	2,1	1,8	1,3	1,0
18	20,7	7,2	3,2	2,7	1,9	1,4
24	27,6	9,6	4,2	3,6	2,5	1,9

Table 15: Temperature increase and operation duration of respective CHP units for various heat quantities stored in a 750 liter buffer tank.

6. On-site energy management using home automation

In this section, the motivation for on-site energy management is presented as well as concrete measures (actions) and the technical implementation by means of a cost-effective home automation system. The term ‘on-site energy management’ refers to any action that aims at phasing the electricity and heat generation of the CHP system to the electricity and heat consumption of the building. It includes power modulation of the CHP unit as well as heat storage in the buffer tank and shifting temporally the electricity and heat consumption of the building.

The options and measures for on-site energy management are discussed under the following conditions:

- In the multy-family homes, the electricity consumption profile is fixed and cannot be influenced because there is no financial incentive for the tenants living in the building to change their consumption habits for energy management reasons.
- In contrast, the nano-CHP systems are owned and operated by the residents of the respective building. Hence, they will benefit in full from any gains that result from energy management measures. Consequently, the financial incentives for changing consumption habits are considerably higher.

6.1. Motivation for on-site energy management in residential buildings

6.1.1. Micro-CHP systems in multi-family homes

1. Assure a profitable operation of the micro-CHP system
   The CHP unit is only run in periods with sufficient electricity self-consumption, i.e. the average electricity demand of the building must exceed a certain level (for the ecoPower 4.7 micro-CHP system this threshold is determined as ≈ 2,500 W as shown in section 4.2.4).
2. Reduce the number of startings and shutdowns of the CHP unit in order to reduce wear
3. Extend the operating time of the CHP unit in order to generate a larger share of the building’s electricity consumption
4. Obtain additional revenues and provide ancillary services (balancing power) to the electricity network by power modulation according to signals received from the network operator

6.1.2. Nano-CHP systems in single family homes, twin-houses or end-terrace houses

1. Assure a profitable operation of the nano-CHP system
   The CHP unit is only run in periods with sufficient electricity self-consumption so that the expenses for natural gas purchase and maintenance can be covered. For the ecoPower 1.0 nano-CHP system a

minimum building electricity demand of ≈ 475 W is necessary in order to avoid financial losses by operating the CHP unit (see section 4.3.1).

2. Increase self-consumption of the generated electricity as much as possible

6.2. Measures for realization of on-site energy management in residential buildings

6.2.1. Micro-CHP systems in multi-family homes

The micro-CHP system is integrated into a home automation system which performs the following functions:

- Continuous retrieval of the current electricity consumption of the building and computation of moving averages
- Identifying the hours of the day in which the building's electricity consumption (moving average) is typically above the threshold for profitable operation of the CHP unit
- Continuous retrieval of the current temperature in the buffer tank
- Retrieval of the heat output supplied to the building and computation of moving averages (the heat quantity that is hourly supplied to the building)
- Based on this information, the home automation system switches on and off the CHP unit and modulates its electricity and heat generation.

Furthermore, the following more advanced functions can also be performed by the home automation system:

- Reception of signals from the network operator or from the control panel of a virtual power plant in order to accordingly modulate the electricity generation
- Control of the charging and discharging of a storage battery and its state of charge
- Implementation of an advanced heat management which makes use of the thermal inertia of the building. For example, considerable amounts of heat can be stored in the walls and floor slabs of the building by heating the room air slightly higher than the desired value. At a later point of time, this heat can be released by lowering the room air temperature slightly below the desired value.

6.2.2. Nano-CHP systems in single family homes, twin-houses or end-terrace houses

The nano-CHP system is also integrated into a home automation system that assures profitable operation by switching on/off the CHP unit as described above for the micro-CHP systems.

However, power modulation is not possible for $1kW_{el}$ nano-CHP units. Instead, the home automation system in buildings with nano-CHP systems needs to include **plug adapters** that can switch on flexible household appliances (like washing machines or dishwashers) when the nano-CHP unit is operating in order to increase self-consumption of the generated electricity. In the same way, the flexible household appliances are switched off when the CHP unit does not operate (or when the electricity consumption of the building is considerably higher than 1000 W). The plug adapters communicate via radio communication with the home automation system.

The calculations in section 5.5 have shown that the heat storage capacity of a 750 L buffer tank as installed in the buildings evaluated in this paper provides large flexibility for operating the CHP unit according to the electricity demand of the building (electricity-oriented CHP unit operation).

As the number of flexible household appliances – as well as their electricity consumption which can potentially be shifted by the plug adapters described above – is relatively low in most buildings inhabited by one family, also a **visualization** was made available to the residents. The visualization illustrates the current electricity flows in the building by means of an app and / or website. Knowing about the current CHP status (ON / OFF) and the electricity feed-in into the grid, the residents can decide to run their electrical appliances during CHP operation and, thus, increase electricity self-consumption. They also receive feedback about their daily, weekly and monthly electricity generation, consumption, purchase from and feed-in into the grid.

Furthermore, in the buildings which are inhabited by only one family the app and / or website should offer the possibility to manually switch on the CHP unit (for instance, before the residents are going to use the electric kitchen stove). Besides, it should enhance energy efficiency by automatically deactivating the radiators when the windows are opened.

6.3. Home automation system

The on-site energy management is realized by a cost-effective and manufacturer-independent **home automation system** on the basis of the open-source software openHAB. The home automation system basically consists of

- sensors that measure temperature, CO_2 concentration and humidity of the room air,
- window contacts that detect whether the window is open or closed,
- an attachment for the thermostatic valve of the radiators that controls the heat output of the radiator and
- the plug adapters mentioned above,

all of which are connected via WLAN or radio communication to the central control unit of the home automation system. In our project, the central control unit is the single-board computer Odroid-U3 which stores all measurement data in a local data base, processes the data and controls the thermostatic valves of the radiators. The Odroid-U3 single-board computer is also connected to the Internet via the WLAN of the residents and transfers the measuring data to a data base at Ruhr West University.

By means of the room air sensors and the thermostatic valve attachments the temperature of each room can be controlled and regulated individually (single room temperature control). In this manner, also the temperature of the walls and floor slabs can be indirectly influenced for the sake of including them into an advanced heat management as mentioned above. The information of the window contacts is used in order to deactivate the radiators in the room in which the window is open: by closing the thermostatic valves heat energy is saved and the energy consumption of the building is reduced.

Finally, the CHP unit is also integrated into the home automation system, i.e. its operating times are controlled by the Odroid-U3 according to the electricity and heat requirements in the building. For this purpose, a PLC (programmable logic control) has been installed in each building. The PLC records the electricity generation of the CHP unit as well as the electricity feed-in into the grid and the electricity purchase from the grid in 1-min intervals by reading out the respective electricity meters; the electricity consumption of the building is calculated from these values. In addition, the PLC also records the temperature at the bottom, in the middle and at the top of the buffer tank. All this data is made available to the residents by means of an app or website. The home automation system also permits the residents to set their desired values or profiles for the room air temperature in each room.

7. Summary, conclusions and outlook

Combined heat and power (CHP) generation in highly efficient CHP systems on the basis of natural gas is the most climate-friendly way of using fossil fuels. Regarding the CHP systems applicable in residential buildings, a distinction is made with regard to the rated electrical power between micro-CHP systems (P_{el} > 2.5 kW) and nano-CHP units (P_{el} < 2.5 kW).

This paper analyzes the performance and the economic feasibility of micro- and nano-CHP systems in different types of residential buildings. In a first step, the economic feasibility for applying micro- and nano-CHP systems in residential buildings is examined in section 4 with respect to the economic and regulatory conditions in Germany in the year 2015. Secondly, the conventional heat-led operation of the CHP systems is evaluated in chapter 5 in the buildings under evaluation. Based on these analyses, in chapter 6 the authors examine various options for operation and profitability enhancement of the CHP systems by means of a novel CHP operation mode ('electricity oriented CHP operation') and energy management in the building.

The research work is carried out within the research project "From laboratory to demonstration: CHP pilot project for CO_2 reduction in the InnovationCity Bottrop". The analyses presented in this paper are based on 1 micro-CHP system and 5 nano-CHP systems which have been installed in different types of residential buildings in Bottrop:

- The micro-CHP system (*Vaillant ecoPower 4.7*) is installed in a multi-family home (MFH).
- Four nano-CHP systems with Stirling engine (*Brötje EcoGen WGS 20.1* and *Viessmann Vitotwin 300W*) are installed in twin-houses or end-terrace houses (TH).
- One nano-CHP system with Otto engine (*Vaillant ecoPower 1.0*) is installed in a single-family home (SFH).

Investigation period are the 7 months from December 2014 to June 2015. In order to determine the optimal operation strategy for each CHP system, a cash flow analysis (on the basis of a full cost accounting) is carried out in **section 4** for an hour of operation of each CHP unit. Heat and electricity generation by the CHP unit competes with heat generation by a state-of-the-art gas condensing boiler (η_{th}=95%) and electricity purchase from the grid (26 ct/kWh_{el}).

For all CHP units, the **economic feasibility** is highly dependent on the self-consumption rate of the generated electricity due to the following reason: the economic value of 1 kWh_{el} consumed by the building is 26 cent (= avoided electricity purchase from the grid) whereas the economic value of 1 kWh_{el} fed into grid is only about 4 cent (average EEX baseload price as compensation for electricity feed-in + compensation for avoided power network use). In addition to these figures and regardless of how the electricity is used, the operator of the CHP system receives a CHP bonus of 5.41 cent for each kWh of generated electricity and a refund of energy tax for the natural gas consumed by the CHP unit.

Cash flow analysis shows that the micro-CHP unit *Vaillant ecoPower 4.7* can cover all cost elements (natural gas purchase, maintenance and depreciation) when the (average) electricity demand of the building is at least 2400 W during the operation period of the CHP unit, corresponding to an electricity self-consumption rate of approx. 52%. The maximum economic advantage at 100% self-consumption is about 50 cent per hour compared to the reference heating system plus electricity purchase from the grid (Fig. 3, Tab. 6). At a given electricity demand between 2400 W and 4700 W ($P_{el,max}$), power modulation does not change considerably the profitability of the CHP unit. However, power modulation can be promising due to the following reasons:

- possibly lower wear and longer service life of the combustion engine at lower engine speeds,
- possibly reduced number of switching-on and switching-off procedures and
- supply of balancing power within a virtual power plant.

The nano-CHP systems, however, are economically not fully competitive with the conventional way of energy supply by the chosen reference system: while the operation expenses (natural gas purchase and maintenance) can be overcompensated by the value of the generated electricity and heat, the investment expenses can not be earned in full by a nano-CHP system. For the *Vaillant ecoPower 1.0* nano-CHP unit, an average electricity demand of the building of just under 500 W (approx. 50% electricity self-consumption) is necessary in order to compensate for the operation expenses.

In contrast, it is not possible to state precise figures for the nano-CHP systems with Stirling engine: the reason is that the full-service contract offered by the Brötje Group involves a fixed annual payment of 390 €. Hence, the effective maintenance cost per operating hour of the *Brötje EcoGen WGS 20.1* nano-CHP unit depends highly on the number of operating hours per year: it amounts to 11 ct/h_{op} at 3,500 h_{op}/a and to 19.5 ct/h_{op} at 2,000 h_{op}/a. The resulting minimum electricity self-consumption which (on average) is needed in order to compensate for the operation expenses is 26.5% at 3,500 h_{op}/a and 66% at 2,000 h_{op}/a.

For the *Viessmann Vitotwin 300W* nano-CHP unit, the authors cannot specify the maintenance cost because the terms of a full-service contract are not defined by the Viessmann Group but by the installers of the CHP system. Therefore, in this paper, the terms of the Brötje full-service contract are also assumed for the Viessmann nano-CHP system.

In **section 5**, the **performance of the CHP systems in classical heat-led operation** is analyzed based on the measuring data. The analyses show that electricity self-consumption is very different among the buildings with nano-CHP system (twin-houses / end-terrace houses and single-family home): the monthly self-consumption rates range from 22% to 87% (Tab. 11); for the multi-family home data is not available. While in two of the buildings self-consumption is larger than 60% in every month of the investigation period, it is less than 48% in every month in the other three buildings with nano-CHP system.

Under the conditions of the field test, the overall efficiencies of the CHP systems are detected considerably lower than the specified values in the data sheets of the manufacturers (Tab. 13). For both Vaillant CHP systems, the overall efficiency is measured about 10% lower than specified: at approx. 82% for the *ecoPower 1.0* nano-CHP system (data sheet: 92%) and at approx. 80% for the *ecoPower 4.7* micro-CHP system (data sheet: 90%), respectively. The nano-CHP systems with Stirling engine reach an overall efficiency of 78.5%, 83.5% and 85.5% (data sheet: 92%). In the summer month of June the findings are slightly distinct: first of all, the overall efficiency in all buildings drops compared to the months up to May and, secondly, the larger *ecoPower 4.7* has a higher overall efficiency (76%) than the smaller *ecoPower 1.0* CHP system (73%).

The electrical efficiency of the entire CHP system, i.e. the ratio of electricity generation to gas consumption, depends on two factors: the electrical efficiency of the CHP unit (which is mainly determined by the electrical efficiency of the combustion engine) and the contribution of the auxiliary heating unit to heat generation (as the auxiliary heating unit does not produce any electricity, but contributes to the gas consumption of the CHP system).

On average, the highest monthly electrical system efficiencies are detected for the *ecoPower 4.7* micro-CHP system installed in the multi-family home (MFH) and reach about 16% – 17%; the maximum is recorded in December at 19% (Tab. 13). In the single family home (SFH) with the *ecoPower 1.0* nano-CHP system, the absolute monthly maximum of all CHP system is registered in June at 21%. However, within the winter period from December to March, the electrical efficiency of the *ecoPower 1.0* nano-CHP system (1 kW_{el}, 2.5 kW_{th}) drops to approx. 10% because of the large heat contribution by the auxiliary heating unit to the building's heat demand (Tab. 13).

Regarding the nano-CHP systems with Stirling engine (1 kW_{el}, 5.6 kW_{th}), the electrical system efficiency changes hardly or not at all between winter and summer months – indicating that the auxiliary heating unit does not contribute substantially to the heat supply of the respective buildings. The monthly electrical efficiency of the Stirling nano-CHP systems ranges between 11% and 13% in two of the buildings and reaches about 9% and 7% in the other two buildings (Tab. 13).

Based on the analyses in sections 4 and 5, the **potential for CHP operation and profitability enhancement** is examined in **section 6** for each type of building and CHP system. Subsequently, an individual on-site energy management strategy is devised for each building and CHP system type. The term 'on-site energy management' refers to all measures that aim at phasing the electricity and heat generation of the CHP system to the electricity and heat consumption of the building.

The **concept of 'electricity oriented operation'** was introduced in sections 2 and 6 as a novel operating strategy for the CHP unit. The electricity oriented operation mode is made up of four components:

- fulfilling the condition for the classical heat-led operation of the CHP unit: a sufficiently low temperature in the buffer tank
- assuring that the minimum level of electricity self-consumption is reached, i.e. the CHP unit is run only in periods with (on average) sufficient electricity demand in the building in order to prevent financial losses for the operator of the CHP system
- if feasible, the operating times of the CHP unit are shifted towards the hours with highest electricity consumption in the building in order to maximize electricity self-consumption
- if the CHP unit is designed for power modulation, the output of the CHP unit is adjusted according to the electricity and heat demand of the building and, potentially, also according to external requirements by the electricity network operator or the control centre of a virtual power plant

In general, the potential and the challenges for energy management differ considerably for the different types of buildings and CHP systems. In **multi-family homes (MFH) with micro-CHP system**, the option of modulating the power of the CHP unit is most promising for energy management: by modulating the electricity and heat generation according to electricity and heat demand of the building, the rate of electricity self-consumption as well as the profitability of the CHP system can be enhanced; the number of startings and shutdowns can be reduced.

Furthermore, the micro-CHP system can be integrated into a virtual power plant. In this case, the electricity generation is also modulated according to external requirements received from the control panel of the virtual power plant or from the electricity network operator. As part of a virtual power plant, the micro-CHP system can participate in the balancing energy market and obtain additional revenues. Additional revenues become increasingly important – apart from the fact that the progres.nrw subsidy is obtainable for new CHP systems only until 31st Dec 2015 – because in the course of the German energy transition ('Energiewende')

- in recent years the EEX baseload price has dropped considerably which determines the compensation for electricity feed-in into the grid and
- the demand for balancing energy increases. [18]

A limiting factor for flexible electricity generation is heat storage capacity of the buffer tank: in view of the high thermal power of the *ecoPower 4.7* micro-CHP unit (12.5 kW_{th}), the heat storage capacity of the 750L buffer tank corresponds to the heat quantity which is generation by the CHP unit in about 2 hours of operation (Tab. 6). Hence, in order to gain additional operation flexibility, the option of making use of the thermal inertia of the building is interesting in MFH because considerable heat quantities can be stored in the substance of a building (like walls, floor slabs etc.) by slightly increasing the temperature of the building substance (via slightly increased room air temperatures). The key challenge of this particular heat management strategy is to avoid compromising the heat comfort of the residents.

For the nano-CHP systems installed in **single family homes (SFH) or end-terrace houses (TH)**, however, power modulation is not possible. Hence, the first step of on-site energy management is to shift the operating times of the CHP unit into the periods of highest electricity consumption in the building. The necessary flexibility for this CHP operation shift is gained from the heat storage capacity of the 750L buffer tank which corresponds to the heat generation within

- approx. 10 operating hours of the *ecoPower 1.0* nano-CHP unit (2.5 kW_{th}) and
- approx. 4 operating hours of the nano-CHP units with Stirling engine (5.6 kW_{th}). (Tab. 6)

The second step of on-site energy management in buildings with nano-CHP system is to adapt the electricity consumption of the building as much as possible to the electricity generation of the CHP unit by the following two actions:

1. Flexible household appliances are turned on/off automatically by plug adapters in a way that maximizes electricity self-consumption and minimizes electricity feed-in into the grid.
2. The residents of the buildings are provided with information about the current levels of electricity generation, consumption and feed-in – all of which are displayed by an app or website – so that they can preferably run their electrical appliances in the times of CHP operation in order to increase electricity self-consumption and, thus, the profitability of their nano-CHP system.

The on-site energy management is realized by a cost-effective and manufacturer-independent **home automation system** on the basis of the open-source software openHAB. The home automation system basically consists of

- sensors that measure temperature, CO_2 concentration and humidity of the room air,
- window contacts that detect whether the window is open or closed,
- an attachment for the thermostatic valve of the radiators that controls the heat output of the radiator and
- the plug adapters mentioned above,

all of which are connected via WLAN or radio communication to the central control unit of the home automation system. In our project, the control unit is the single-board computer Odroid-U3 which stores all measurement data in a local data base, processes the data and controls the thermostatic valves of the radiators. The Odroid-U3 single-board computer is also connected to the Internet via the WLAN of the residents and transfers the measuring data to a data base at Ruhr West University.

By means of the room air sensors and the thermostatic valve attachments the temperature of each room can be controlled and regulated individually (single room temperature control). In this manner, also the temperature of the walls and floor slabs can be indirectly influenced for the sake of including them into an advanced heat management as mentioned above. The information of the window contacts is used in order to deactivate the radiators in the room in which the window is open: by closing the thermostatic valves heat energy is saved and the energy consumption of the building is reduced.

Finally, the CHP unit is also integrated into the home automation system, i.e. its operating times are determined by the Odroid-U3 according to the electricity and heat requirements in the building. For this purpose, a PLC (programmable logic control) has been installed in each building. The PLC records the electricity generation of the CHP unit as well as the electricity feed-in into the grid and the electricity purchase from the grid in 1-min intervals by reading out the respective electricity meters; the electricity consumption of the building is calculated from these values. In addition, the PLC also records the temperature at the bottom, in the middle and at the top of the buffer tank. All this data is made available to the residents by means of an app or website. The home automation system also permits the residents to set their desired values or profiles for the room air temperature in each room.

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Test Methods

Laboratory Measurements and Diagnostics of Residential HVAC Installation and Maintenance Faults

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Abstract

Laboratory measurements of residential HVAC installation and maintenance faults are provided for a 13-SEER split-system air conditioner. Test conditions differ from those used to rate cooling systems to emulate typical installations in California. Equipment was set up in three chambers to model indoor, outdoor, and hot-attic conditions. Tests were conducted using TXV and non-TXV metering devices. Results are provided for low airflow, coil blockage, refrigerant over/under charge, duct leakage, ducts/equipment in hot-attic conditions, improper TXV sensing-bulb installation, non-condensables, and restrictions. Baseline tests using the "code tester" instead of forced-air unit (FAU) are only 3% less than the 13 SEER (Seasonal Energy Efficiency Ratio) with ducts, evaporator, and FAU located in conditioned space. The SEER* is 8% less with FAU in conditioned space. With ducts, evaporator, and FAU in hot-attic conditions, the Energy Efficiency Ratio* (EER*) is 11% less and SEER* is 23% less. Moderate to severe non-condensables reduce efficiency by 12 to 38% and increase power by 8 to 22%. Refrigerant restrictions reduce efficiency by 30 to 59%. Multiple faults including low airflow, undercharge, duct leakage, and condenser-coil blockage reduce EER* by 54% and SEER* by 67%. While laboratory tests of RCA faults indicate generic protocols can yield false alarms, misdetection or misdiagnosis, they were 100% accurate evaluating refrigerant charge faults when no other faults were present and 74% to 89% accurate overall. It took 45 minutes to test for 1% non-condensables where condenser temperature is at least 2C above 35C outdoor temperature. If significant refrigerant-system faults are detected manufacturers recommend recovering charge, making corrections, evacuating to 66.6 Pa, and weighing in factory charge.

Introduction

Residential and commercial heating, ventilating, and air conditioning (HVAC) consumption in the United States accounts for 30% of average summer peak-day electricity loads, 13% of total electricity use, and 44% of total natural gas use [16]. A 2002 study published by the Hewlett Foundation indicates that improved HVAC installation and maintenance represents one of the largest economically achievable opportunities for energy efficiency savings [15]. This paper provides laboratory test results of a new 3-ton (10.55 kW) split-system 13-SEER air conditioner using R-22 refrigerant. Test conditions differ from those used to rate cooling systems to match typical installations in California. The equipment was set up in three chambers to simulate both AHRI 210/240 indoor and outdoor conditions and hot attic conditions. Laboratory test results are provided for HVAC faults that occur due to installation and maintenance deficiencies and degradation. Tests were conducted using thermostatic expansion valve (TXV) and non-TXV piston metering devices. Test results are provided for the following faults: uninsulated TXV sensing bulb, low airflow, ducts and equipment in 118°F (65.6C) hot attic, evaporator/condenser coil blockage, duct leakage, improper refrigerant charge, non-condensables, and restrictions.[1]

The tests were performed to support California energy efficiency programs promoting quality installation and maintenance in order to evaluate the effectiveness of refrigerant charge diagnostic protocols, measurement tools, and procedures [1]. Some programs rely on the California Energy Commission (CEC) refrigerant charge and airflow (RCA) protocol which requires verification of subcooling (SC) for TXV units or superheat (SH) for non-TXV units [5]. Other programs rely on

[1] The 118F (48C) hot attic temperature is 3°F (1.7C) less than 122°F (68C) maximum for black shingles, radiant barrier, and 1:150 enhanced ventilation and 18°F (10C) less than black shingles, radiant barrier and 1:300 standard ventilation [12].

proprietary protocols.[2] Yuill and Braun evaluated the CEC RCA protocol and reported 41% correct diagnosis for non-TXV and 64% correct diagnosis for TXV equipped systems [19]. Laboratory tests and field observations of technicians indicate that generic RCA protocols, inaccurate tools, and improper procedures can cause false alarms, misdetection, and misdiagnosis [11]. Laboratory tests of unit-specific manufacturer refrigerant charge (RC) protocols indicate fewer problems diagnosing refrigerant charge faults when no other faults are present due to wider tolerances and multi-step procedures [11]. Nevertheless, both types of protocols have limitations and neither can diagnose refrigerant charge faults from non-condensables, restrictions, condenser or evaporator heat transfer issues, low airflow, or expansion valve failure.

Test Equipment Laboratory Setup

The tested split-system air conditioning equipment is a nominal 3-ton (36,000 Btu/hr or 10.55 kW) unit with a Seasonal Energy Efficiency Rating (SEER) of 13 and an Energy Efficiency Rating (EER) of 11.2 when equipped with a hard shut-off (HS) TXV, time delay relay (TDR), and R-22 refrigerant.[3] A manifold with isolation valves was used to test the HS-TXV and non-TXV (piston) expansion devices commonly found on older equipment. Outlet tubes from the expansion devices merged to supply liquid refrigerant to the evaporator coil. The outdoor unit consists of a condenser, compressor, and condenser fan. The indoor unit consists of an evaporator coil, FAU, and appropriate supply and return ducts to connect the unit to measurement equipment and the indoor chamber conditions. The equipment was manufactured in 2010, but is currently unavailable in the United States due to the phase out of R-22 refrigerant.

Laboratory tests were conducted according to AHRI Standard 210/240-2008 with modifications to obtain "application" Energy Efficiency Ratio* (EER*) and Seasonal Energy Efficiency Ratio (SEER*) [2].[4] Test modifications include locating ducts, evaporator, and FAU in hot attic conditions of 118°F (65.6C) dry-bulb and 78°F (43.3C) wet-bulb temperature to simulate typical peak cooling applications in California and other hot climates where ducts are located in unconditioned attics. Test modifications also included duct leakage on supply and return ducts, longer ducts with bends typical of field installations, and line-set lengths of 25 feet (7.62 m) and 50 feet (15.24 m) between the condenser and evaporator. The unit was also tested with equipment located in conditions of 80°F (44.2C) dry-bulb and 67°F (37.2C) wet-bulb (per the AHRI 210/240 test).[5] The "application" efficiency ratings are the combined equipment plus distribution system efficiency typical of California residential applications, but not equivalent to published AHRI ratings. The air conditioning equipment was tested with its AHRI-rated configuration including HS-TXV with copper sensing bulb/strap, 25-feet (7.62 m) line set and test chamber "code tester" fan to verify the rating [3].[6] The unit was also tested with an HS-TXV with stainless-steel sensing bulb/strap and non-TXV.

Tests were performed at an AHRI-certified laboratory located in the United States. The laboratory is used by manufacturers to certify air conditioners and heat pumps for AHRI testing. The test facility consists of climate-controlled indoor, outdoor, and hot attic chambers where ducts, evaporator, and FAU are located. The air conditioner, liquid-line filter drier, metering devices (TXV and non-TXV), sight glasses, and standard test equipment were assembled and installed in the test chambers by laboratory technicians. Prior to charging with refrigerant, the system was pressurized to 300 psig (2.07 MPa) with nitrogen and held for 60 minutes to absorb moisture and check for leaks. After the nitrogen

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[2] See http://www.ac-quality.com/contractors/about_qm or http://www.hvacoptimization.com/.

[3] AHRI Rating is for the condenser and evaporator pair tested with no FAU, hard shut-off TXV, and TDR that continues fan operation after compressor turns off to recover latent cooling from evaporator and increase efficiency.

[4] The ARI 210/240 EER_A and EER_B indoor air dry-bulb temperature is 80°F (44.2C) and the wet-bulb is 67°F (37.2C). The EER_A outdoor air dry-bulb is 95°F (52.8C). The EER_B outdoor air dry-bulb is 82°F (45.6C). The SEER outdoor air dry-bulb is 82°F, indoor air dry-bulb is 80°F (44.2C), and indoor air wet-bulb is 57°F (31.7C).

[5] AHRI 210/240 prescribes supply air fan power of 0.365W/cfm (0.0129 W/lpm) of supply air with fan heat of 1.250 Btuh/cfm (0.1506 W/lpm). The tested unit supply fan power was 0.470 W/cfm (0.01669 W/lpm).

[6] The "code tester" is the airflow measuring apparatus described in Section 5.3 Test Chambers (Code Testers), ANSI/ASHRAE 41.2-1987 (RA92).

leak test, a vacuum pump was used to evacuate the system to below 500 micron mercury (μHg) (66.6 Pa) vacuum held for 30 minutes (ASHRAE 2010).

Baseline Tests

Unique baseline tests are performed for each set of tests since each setup can cause slight variations between baseline tests. **Table 1** provides a comparison of test findings to the AHRI rating for a typical residential installation. Tests 318-2 were performed with the code-tester fan (no FAU), HS-TXV with copper bulb/strap, and ducts and evaporator located in conditioned space at 80°F dry-bulb and 67°F wet-bulb temperatures. Tests 318-2 measured 11.3 +/- 0.36 EER and 12.63 +/- 0.4 SEER which are within +/-3.2% of the 11.2 EER and 13 SEER rated values.[7] Tests 310 were performed with an HS-TXV with stainless-steel bulb/strap and ducts, evaporator, and FAU in conditioned space causing a 4% reduction in EER^*_A and 8% reduction in SEER* compared to the AHRI rating. Tests 303 were performed with the same equipment as tests 310, but with ducts, evaporator, and FAU in hot attic conditions. Tests 303 have 16% lower EER^*_A and 29% lower SEER* than the AHRI ratings. Comparing tests 303 to 310 shows that locating equipment in hot attic conditions reduces EER* by 11% and SEER* by 23%. Monitoring studies show homes with ducts in hot attics use up to 30% more space cooling energy [7].The manufacturer RC protocol is correct for all tests, i.e., actual SC is within +/-3°F or +/- 1.7C of the unit-specific manufacturer 7°F target.[8]

Table 1. Baseline TXV Tests with Equipment in Conditioned Space and Hot Attic

Description	Duct Leakage	EER^*_A Capacity (Btuh)	EER^*_A	EER^*_A Impact %	Delta SC (°F)	Manufacturer RC Protocol	SEER*	SEER* Impact %	Test
AHRI Rating (no FAU, HS-TXV, TDR)	2%	33,800	11.2		NA	Correct chg	13.0		n/a
Code tester, HS-TXV copper bulb/strap, ducts/evaporator in conditioned space, no TDR	2%	35,607	11.3	1%	3.0	Correct chg	12.63	-3%	318-2
FAU, HS-TXV steel bulb/strap, ducts/evap/FAU in cond. space, no TDR	2%	35,030	10.7	-5%	-0.8	Correct chg	11.9	-9%	310
Above + ducts/evap/FAU in hot attic conditions no TDR	2%	31,054	9.5	-16%	-2.8	Correct chg	9.2	-29%	303

Baseline and multiple fault tests for the non-TXV are presented in **Table 2**. Baseline Tests 300 were performed with ducts, evaporator, and FAU in conditioned space. Tests 189-4 were performed with ducts, evaporator, and FAU in the hot attic chamber. Tests 189-4 have 10% lower EER^*_A and 18% lower SEER* compared to tests 300 (exclusive of duct leakage). Tests 409 were performed with multiple faults including 25% low airflow 10% undercharge, 30% duct leakage, and 50% condenser coil blockage. Tests 409 have 58% lower EER^*_A and 73% lower SEER* than tests 300. The baseline for developing diagnostic tests for non-condensables is referenced to ducts, evaporator, and FAU in hot attic conditions (TXV tests 303 and non-TXV tests 189-4). The CEC RCA protocol indicates an overcharge and low airflow for the baseline tests 300 (80°F cool attic), and correct RCA for the hot attic tests. For the multiple-fault tests the CEC RCA protocol correctly indicates undercharge and low capacity.

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[7] Efficiency values (i.e., EER and SEER) are based on air-side calculations. The uncertainty of EER and SEER calculations is +/-2.8% based on laboratory measurement tolerances and 5.5% based on ANSI/AHRI 210/240 tolerances. S. Klein. 1992. Engineering Equation Solver v8.897. http://www.fchart.com/ees/.

[8] Target subcooling is based on manufacturer data. Subcooling measures the heat removed from refrigerant after it changes to liquid and is defined as the difference between condenser saturation temperature and liquid line temperature. Delta subcooling is the difference between actual and target subcooling.

Table 2. Baseline and Multiple Fault non-TXV Tests w/ Equip. in Cond. Space and Hot Attic

Description	Duct Leakage	EER^*_A Capacity (Btuh)	EER^*_A	EER^*_A Impact %	Delta TS (°F)	Delta SH (°F)	CEC RCA Protocol	SEER*	SEER* Impact %	Test
FAU, non-TXV, no TDR, ducts/evap/FAU in conditioned space, 50 feet line set	2%	34,542	10.5	NA	4.3	-11.3	Over-charge, low airflow	10.8	NA	300
Above + ducts/evap/FAU in hot attic 118°F	2%	31,050	9.4	-10%	2.3	-2.3	Correct RCA	8.9	-18%	189-4
Above + 25% low airflow, -10% charge, 30% duct leakage, 50% cond. coil block	30%	13,731	4.4	-58%	-7.0	30.4	Correct under-charge, low capacity	2.94	-73%	409

Thermostatic Expansion Valve (TXV) Tests

TXV tests were conducted to evaluate sensing bulb insulation. **Table 3** provides insulated and uninsulated TXV sensing bulb test results with correct charge of 102 ounces and 10% to 40% overcharge with 50 feet line set and equipment located in hot attic conditions. The uninsulated TXV sensing bulb causes improper metering of refrigerant and reduces efficiency by 2%. The manufacturer RC protocol provides a false alarm for test 22 and misdetections for tests 35, 38, and 39. Test 42 (+40% charge) is correctly diagnosed. For proper operation the TXV sensing bulb must be at the correct orientation with copper straps and R-1 closed-cell insulation.

Table 3. Insulated and Uninsulated TXV Sensing Bulb Tests with Equipment in Hot Attic

Description	EER^*_A Capacity (Btuh)	EER^*_A	EER^*_A Impact %	Delta SC (°F)	Manufacturer RC Protocol	Test
TXV R-1 insul., correct chg, 102 oz.	31,420	9.60	NA	-0.7	Correct charge	23
TXV uninsulated, correct chg, 102 oz.	30,873	9.41	-2%	-5.4	False alarm UC	22
TXV uninsulated, +10% chg, 112.2 oz	30,237	9.19	-4%	-2.9	Misdetection	35
TXV uninsulated, +20% chg, 122.4 oz	30,075	8.97	-7%	-2.9	Misdetection	38
TXV uninsulated, +30% chg, 132.6 oz	28,676	8.44	-12%	-1.2	Misdetection	39
TXV uninsulated, +40% chg, 142.8 oz	27,754	7.99	-17%	7.3	Overcharge	42

Airflow Tests

Airflow test results are shown in **Table 4** for the non-TXV unit with equipment in hot attic conditions. Airflow tests are performed with refrigerant charge of 108 ounces. Typical in-situ airflow ranges from 160 to 370 cfm/ton with an average of 320 cfm/ton [13]. Lab tests indicate that low airflow reduces EER^*_A by 3 to 12%. The non-TXV tests for this specific unit, demonstrate that low airflow down to 350 cfm/ton (2818 lpm/kW) does not cause false charge diagnostics using the CEC RCA protocol (i.e., delta SH is within +/-5°F or +/-2.8C and delta TS is within +/-3°F or +/-1.7C).[9] Low airflow at 250 cfm/ton (2013 lpm/kW) or less causes misdiagnosed overcharge due to icing of the evaporator coil. The CEC RCA temperature split protocol correctly detects low airflow for test 65 at 302 cfm/ton (2413 lpm/kW) and test 66 at 250 cfm/ton (i.e., delta TS greater than 3°F or 1.7C).[10]

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[9] Target superheat is based on return air wetbulb and condenser entering air drybulb. Delta superheat is the difference between actual and target superheat. Superheat measures the heat added to refrigerant after it changes to vapor and is defined as the difference between suction line temperature and evaporator saturation temperature.

[10] The CEC RCA temperature split (TS) protocol measures the sensible temperature drop across the evaporator coil and compares this value to target temperature split (TTS) to estimate proper airflow assumed to be 350 and 400 cubic feet per

Table 4. Low Airflow Impact on EER* (non-TXV) and Hot Attic

Description	EER*A Capacity (Btuh)	Airflow cfm/ton	EER*A	EER*A Impact %	Delta TS (°F)	Delta SH (°F)	CEC RCA Protocol	Test
Baseline airflow	31,302	391	9.49	NA	2.5	-3.7	Correct RCA	53
10% low airflow	29,501	351	9.19	-3%	2.8	-0.2	Correct RCA	64
23% low airflow	28,538	302	9.04	-5%	4.6	-2.2	Correct RC, low airflow	65
36% low airflow	26,174	250	8.39	-12%	5.4	-6.0	Misdiagnosed OC, correct low airflow	66

Evaporator Coil Blockage Tests

Table 5 provides evaporator coil blockage test results for the non-TXV with 25-feet (7.62 m) line set and ducts, evaporator, and FAU in conditioned space.[11] The Test 8 baseline has refrigerant charge of 78.4 ounces (2.223 kg). Test 10 has 50% evaporator coil blockage which causes 16% low airflow. The EER* is reduced by 5% and delta SH is outside the acceptable +/-5°F or +/-2.8C tolerance. Test 10 shows that 50% evaporator coil blockage causes the CEC RCA protocol to diagnose false overcharge (i.e., delta SH less than -5°F). Test 11 has 50% coil blockage, 16% low airflow and 10% undercharge. The EER* is 7% less than the Test 8 baseline. Test 11 delta SH is 1.0°F (within +/-5°F tolerance) and delta TS is 0.7°F (within +/-3°F tolerance). The CEC RCA protocol does not detect 16% low airflow nor 10% undercharge.

Table 5. Evaporator Coil Blockage Impact on EER* (non-TXV) Equip in Conditioned Space

Description	EER*A Capacity (Btuh)	Airflow cfm/ton	EER*A	EER*A Impact %	Delta TS (°F)	Delta SH (°F)	CEC RCA Protocol	Test
Baseline non-TXV	33,652	400	10.40	NA	0.0	1.1	Correct RCA	8
50% coil blockage, 16% low airflow	31,281	335	9.92	-5%	1.6	-11.1	False overcharge missed detection	10
50% coil blockage, 16% low airflow, -10% chg	30,531	336	9.66	-7%	0.7	1.0	Missed detection	11

Table 6 provides evaporator coil blockage test results for the HS-TXV unit with 25-feet line set and ducts, evaporator, and FAU in conditioned space. The test 1 baseline has refrigerant charge of 86.4 ounces. Test 12 has 50% coil blockage which causes 15% low airflow. The EER* is reduced by 4.2%, but the unit is diagnosed with correct charge since delta SC is -0.1°F and within +/-3°F tolerance. The manufacturer protocol does not detect 15% low airflow.

Table 6. Evaporator Coil Blockage Impact on EER* (HS-TXV) Equip in Conditioned Space

Description	EER*A Capacity (Btuh)	Airflow cfm/ton	EER*A	EER*A Impact %	Delta TS (°F)	Delta SC (°F)	Manufacturer RC Protocol	Test
Baseline TXV	34,205	395	10.24	NA	1.2	2.1	Correct RCA	1
50% coil blockage 15% low airflow	31,239	335	9.81	-4%	1.5	-0.1	Correct charge, missed detection	12

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minute (cfm) per ton (2818 to 3221 lpm/kW). The TTS varies from 8.1 to 25.9°F (4.5 to 14.4C) over a range of return drybulb temperatures of 70 to 84°F (38.9 to 46.7C) and return wetbulb temperatures of 50 to 76°F (27.8 to 42.4C). Delta TS is the difference between actual TS and TTS.

[11] Tests in conditioned space were performed with 25 feet (7.62 m) line-set requiring less refrigerant charge than tests in hot attic conditions with 50 feet (15.24 m) line-set. Evaporator coil was blocked with plastic corrugated cardboard covering 50% of the upstream side of the evaporator cross-sectional area.

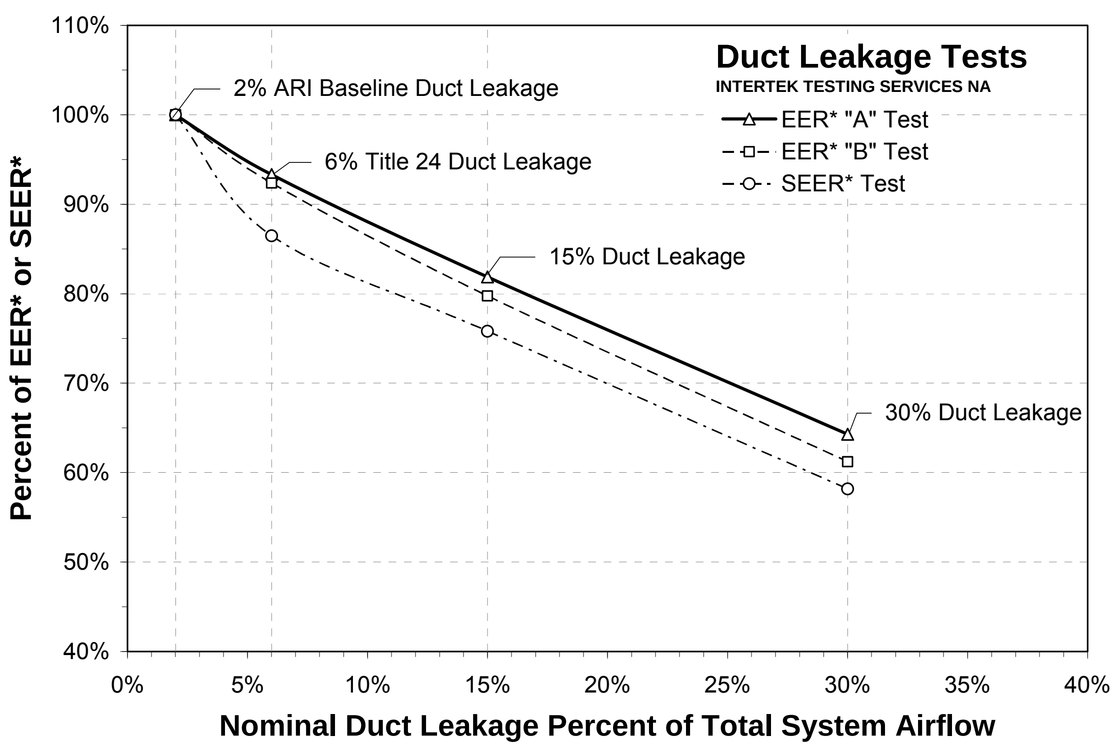
Duct Leakage Tests

Table 7 and **Figure 1** provide duct leakage test results for the non-TXV system with ducts, evaporator, and FAU located in hot attic conditions maintained at 118°F (65.6C). The baseline 2% duct leakage (test 400) is measured at 25 Pascal as the percentage of total system airflow of 300 cfm/ton (2416 lpm/kW) per the modified test procedure (25% low airflow). Duct leakage tests are performed with refrigerant charge of 108 ounces (3.06 kg). The 6% duct leakage test 401 is the compliance value in the California Energy Commission building energy efficiency standards [5]. The 15% duct leakage test 402 was previously the Energy Star target for existing homes. The 30% duct leakage test 403 is common of many US homes [12, 14, 17]. Tests were performed with 50% of duct leakage on the return and supply plenum. Modified AHRI 210/240 tests were conducted to obtain the following unit plus distribution system application efficiencies: EER^*_A, EER^*_B, and SEER*. Tests indicate duct leakage of 6 to 30% reduces efficiency by 7 to 42%. The CEC RCA protocol is correct for all tests except 30% duct leakage (test 403) which is misdiagnosed with undercharge and correct airflow.

Table 7. Duct Leakage Impacts on EER* and SEER* for non-TXV and Hot Attic

Description	EER*A Capacity (Btu/hr)	EER*A	EER*A Impact %	Delta TS (°F)	Delta SH (°F)	CEC RCA Protocol	EER*B	SEER*	SEER* Impact %	Test
Baseline 2% duct leakage	28,670	9.27	NA	5.1	-3.5	Correct RC low airflow	10.62	9.17	NA	400
6% duct leakage	26,804	8.65	-7%	5.7	-3.0	Correct RC low airflow	9.81	7.93	-14%	401
15% duct leakage	23,708	7.59	-18%	4.3	1.3	Correct RC low airflow	8.47	6.95	-24%	402
30% duct leakage	18,736	5.96	-36%	2.1	5.4	Misdiagnosed	6.5	5.33	-42%	403

Figure 1: Laboratory Tests of Duct Leakage on non-TXV Unit



Condenser Blockage Tests

Condenser coil blockage tests are performed with airflow of 400 cfm/ton and refrigerant charge of 108 ounces.[12] Results are shown in **Table 8**. Condenser coil blockage impacts EER^*_A by -4% to -32% and increases total air conditioner power by 3% to 27%. The CEC RCA protocol baseline clean condenser diagnostic is correct. The CEC RCA protocol misdiagnosed condenser coil blockage as an overcharge (OC) for 30 to 80% condenser blockage. The 80% condenser coil blockage test 190-2 has 40.7°F (22.6C) condenser over ambient (COA) defined as the condenser saturation temperature minus condenser entering air temperature. High COA indicates reduced condenser heat transfer (blockage or fan failure), non-condensables, or overcharge. Technicians following the CEC RCA protocol might remove charge from units having condenser heat transfer problems.

Table 8. Condenser Coil Blockage Impact on EER* (non-TXV) and Hot Attic

Description	EER^*_A Capacity (Btu/hr)	EER^*_A	EER^*_A Impact %	Delta TS (°F)	Delta SH (°F)	COA (°F)	CEC RCA Protocol	kW_A	kW_A Impact %	Test
Baseline clean condenser	32,335	9.82	NA	2.6	1.6	15.9	Correct RCA	3.292	NA	189-2
30% condenser blockage	32,136	9.46	-4%	2.7	-8.8	19.3	Misdiagnosed OC	3.397	3%	192-2
50% condenser blockage	31,439	8.94	-9%	2.6	-13.5	23.3	Misdiagnosed OC	3.52	7%	191-2
80% condenser blockage	27,806	6.67	-32%	1.6	-12.8	40.7	Misdiagnosed OC	4.168	27%	190-2

Refrigerant Charge Tests

Table 9 and provides refrigerant charge fault test results for the HS-TXV unit and hot attic conditions of 118°F (65.6C) dry bulb and 78°F (43.3C) wet bulb temperatures. **Figure 2** shows 27 to 56% reduced efficiency with -30 to -40% undercharge but only -15% reduced efficiency with an overcharge of +30 to +40%. The base charge is 102 ounces or 2.89 kg. Tests are performed with airflow from 376 to 387 cfm/ton (3027 to 3116 lpm/kW). Airflow variations are caused by condensation or ice on the evaporator coil. The HS-TXV EER* performance is severely impacted by under charge. The manufacturer protocol correctly diagnoses all of the refrigerant charge fault tests.

Table 9. Refrigerant Charge Impacts on EER* and kW_A for HS-TXV and Hot Attic

Description	EER^*_A Capacity (Btu/hr)	EER^*_A	EER^*_A Impact %	kW^*_A	kW_A Impact %	Delta SC (°F)	COA (°F)	Manufacturer RC Protocol	Test
Base charge 102 oz.	31,420	9.60	NA	3.28	NA	-1.0	14.6	Correct charge	23
+10% charge 112.2 oz.	31,796	9.24	-4%	3.44	5%	12.9	22.4	Overcharge	36
+20% charge 122.4 oz.	31,730	8.84	-8%	3.59	9%	18.9	27.8	Overcharge	37
+30% charge 132.6 oz.	31,321	8.12	-15%	3.86	18%	22.3	31.6	Overcharge	40
+40% charge 142.9 oz.	30,796	8.01	-17%	3.84	17%	24.4	34.3	Overcharge	41
-10% charge 91.8 oz.	29,200	9.22	-4%	3.17	-3%	-7.1	10.7	Undercharge	45
-20% charge 81.6 oz.	25,826	8.28	-14%	3.12	-5%	-7.4	9.1	Undercharge	48
-30% charge 71.4 oz.	21,170	6.98	-27%	3.03	-8%	-7.5	6.7	Undercharge	49
-40% charge 61.2 oz.	12,242	4.24	-56%	2.89	-12%	-6.3	2.6	Undercharge	52

[12] Condenser coil was blocked with plastic corrugated cardboard covering 50 to 80% of the inlet cross-sectional area. Field tests of dirty condenser coils verified the test setup based on similar condenser pressure impacts.

Figure 2: Laboratory Tests of Refrigerant Charge Faults on TXV Unit

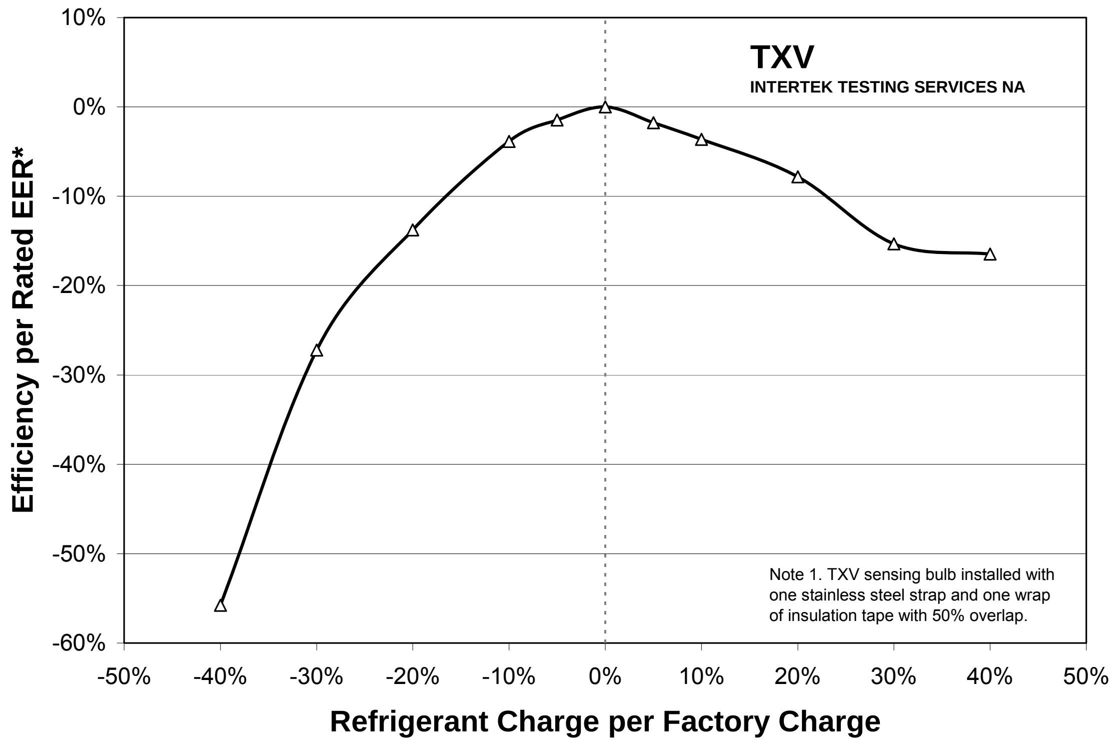
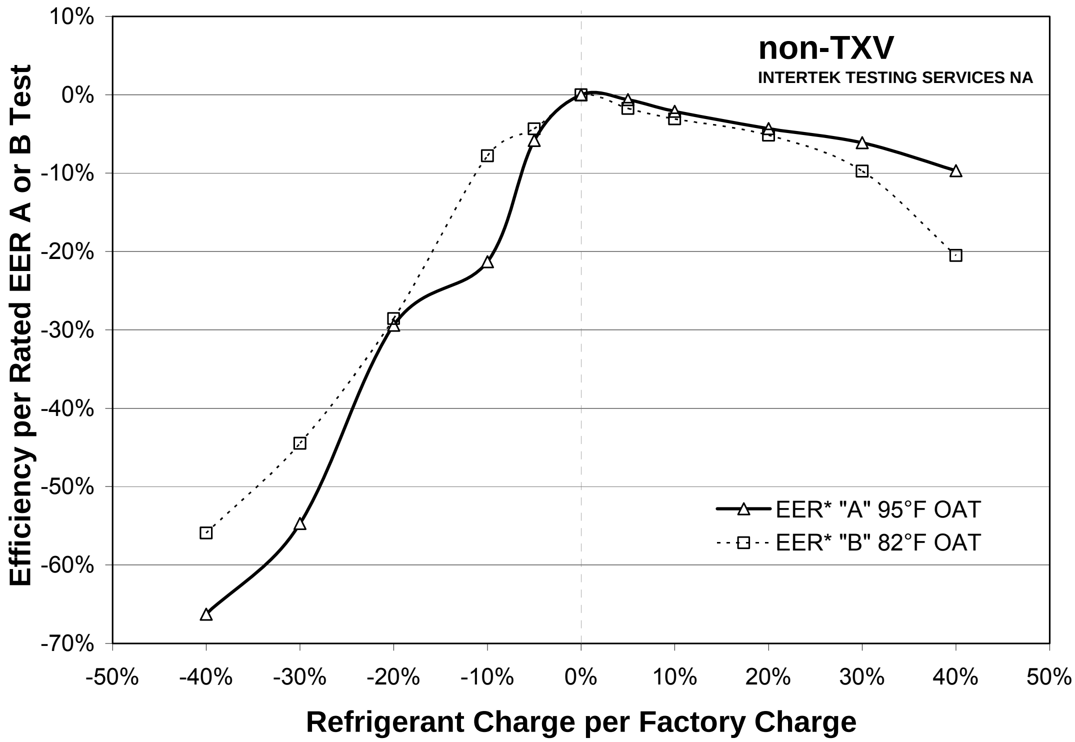


Table 10 provides refrigerant charge test results for the non-TXV piston and hot attic conditions of 118°F (65.6C)dry bulb and 78°F (43.3C) wet bulb temperatures. The base charge is 108.2 ounces or 3.067 kg. Tests are performed with airflow from 364 to 395 cfm/ton (2931 to 3180 lpm/kW). Airflow variations are caused by condensation or ice on the evaporator coil. Non-TXV EER* performance is severely impacted by undercharge similar to the TXV. The CEC RCA protocol correctly diagnoses all of the refrigerant charge fault tests. Laboratory Tests of Refrigerant Charge Faults on non-TXV Unit **Figure 3** shows 55 to 66% reduced efficiency with -30 to -40% undercharge but only 6 to 10% reduced efficiency with +30 to +40% overcharge.

Table 10. Refrigerant Charge Impacts on EER* and kW$_A$ for non-TXV and Hot Attic

Description	EER*$_A$ Capacity (Btu/hr)	EER*$_A$	EER*$_A$ Impact %	kW*$_A$	kW$_A$ Impact %	Delta TS (°F)	Delta SH (°F)	COA (°F)	CEC RCA Protocol	Test
Base charge 108.2 oz.	31,302	9.49	NA	3.30	NA	2.5	-4.4	17.7	Correct RCA	53
+10% charge 119 oz.	31,600	9.29	-2%	3.40	3%	2.9	-13.4	20.1	Overcharge	60a
+20% charge 129.8 oz.	31,013	9.08	-4%	3.42	4%	3.3	-13.4	20.4	Overcharge	61a
+30% charge 140.6 oz.	30,765	8.91	-6%	3.45	5%	2.7	-13.4	21	Overcharge	62
+40% charge 151.5 oz.	30,526	8.57	-10%	3.56	8%	2.6	-13.4	21.9	Overcharge	63
-10% charge 97.4 oz.	23,352	7.47	-21%	3.13	-5%	-3.5	28.8	10.1	Undercharge	55
-20% charge 86.6 oz.	20,371	6.70	-29%	3.04	-8%	-5.8	37.9	8.4	Undercharge	56a
-30% charge 75.8 oz.	12,629	4.30	-55%	2.94	-11%	-9.4	50.8	4.7	Undercharge	57a
-40% charge 64.9 oz.	9,186	3.20	-66%	2.87	-13%	-10.8	57.6	2.9	Undercharge	58

Figure 3: Laboratory Tests of Refrigerant Charge Faults on non-TXV Unit



Non Condensable Tests

If proper vacuum is not achieved at installation the refrigerant system will be contaminated with non-condensable air and water vapor which can cause compressor failure. Non-condensables (NC) decrease condenser heat transfer and cooling capacity and increase condenser pressure and power input. **Table 11** provides laboratory test results for 0.3 oz or 0.0085 kg (~0.3% of system charge by weight) of non-condensable nitrogen on the unit operating with the HS-TXV and hot attic conditions.[13] Tests are performed with airflow from 385 to 400 cfm/ton (3100 to 3221 lpm/kW) and refrigerant charge of 102 ounces or 2.89 kg. The impact is -13% for EER^*_A, +6% for kW^*_A, and -13% for $SEER^*$. The manufacturer RC protocol misdiagnoses non-condensables as an overcharge for test 505.

Table 11. Non-condensable Impacts on EER* and SEER* for TXV and Hot Attic

Description	EER^*_A Capacity (kBtuh)	EER^*_A	EER^*_A Impact %	kW^*_A	kW_A Impact %	Delta SC (°F)	COA (°F)	Manufacturer RC Protocol	$SEER^*$	$SEER^*$ Impact %	Test
Baseline	31,054	9.48	NA	3.28	NA	-2.7	13.7	Correct	9.21	NA	303
0.3% NC	27,373	8.27	-13%	3.48	6%	15.0	25.9	Misdetection	7.98	-13%	505

Table 12 provides results for 0.3 oz (~0.3% system charge) of non-condensable nitrogen on the non-TXV unit. Tests are performed with airflow from 396 to 400 cfm/ton and refrigerant charge of 108 ounces or 3.06 kg. The impact of 0.3% non-condensables is -18% for EER^*_A, +8% for kW^*_A, and -19% for SEER*. The impact of ~1% non-condensables (Test 501X) is -38% for EER^*_A and +28% for

[13] The 0.3 ounces (0.0085 kg) or 0.3% non-condensable is based on nitrogen in an improperly evacuated 15-feet line set (4.572 m) (262 in^3 or 0.004293 m^3) plus evaporator coil volume (200 in^3 or 0.003297 m^3) times the density of nitrogen at 6.535 x 10^{-4} oz./in^3 (1.1234 kg/m^3).

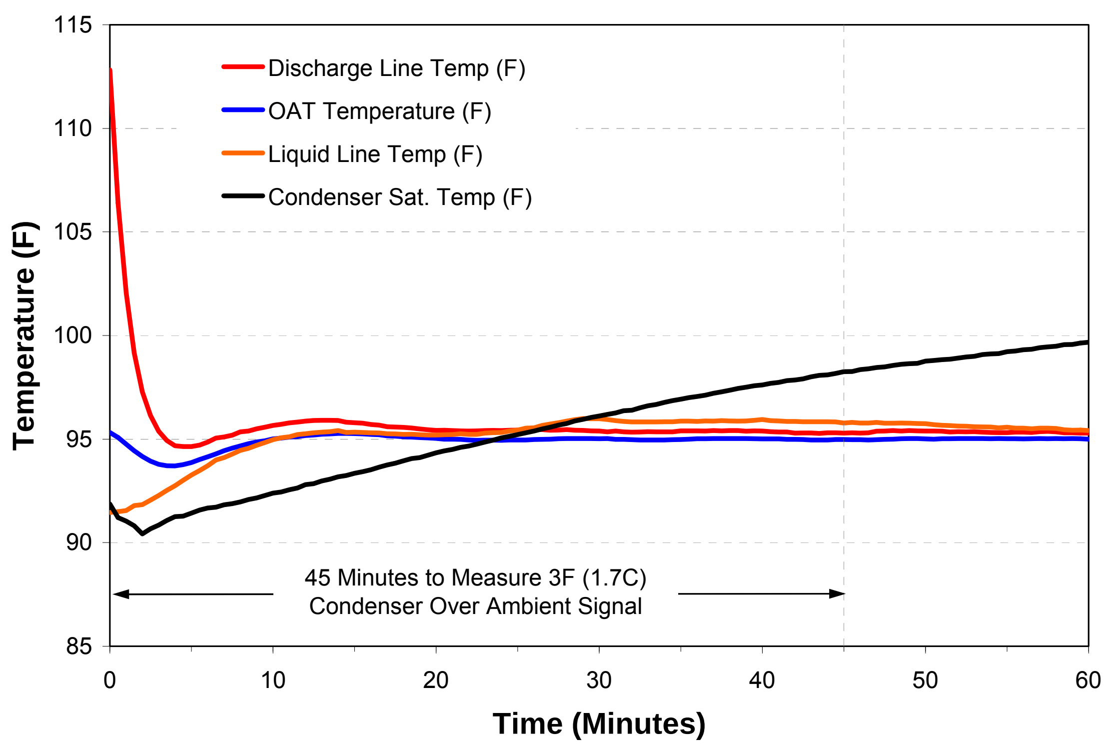
kW_A. The CEC RCA protocol misdiagnoses non condensables as a false undercharge for test 501 with 0.3% NC and 501X with ~1% NC. Split-system air conditioners are often evacuated with time-based procedures without a vacuum pressure gauge. Field observations indicate that many vacuum pumps have contaminated oil [11]. Changing oil after every evacuation is required to achieve proper evacuations [8]. Performing a vacuum to 240 μHg (32 Pa) held at or below 500 (66.7 Pa) to 1000 μHg (133.32 Pa) for 30 minutes will remove non-condensables [4].

Table 12. Non-condensable Impacts on EER* and SEER* for non-TXV and Hot Attic

Description	EER^*_A Capacity (kBtuh)	EER^*_A	EER^*_A Impact %	kW^*_A	kW_A Impact %	Delta SH (°F)	COA (°F)	CEC RCA Protocol	$SEER^*$	$SEER^*$ Impact %	Test
Baseline	31,050	9.42	NA	3.30	NA	2.1	16.1	Correct chg	8.86	NA	189-4
0.3% NC	27,373	7.71	-18%	3.55	8%	10.5	28.9	Misdiagnosis	7.22	-19%	501
~1% NC	20,486	5.87	-38%	4.21	28%	4.0	46.8	Misdiagnosis	NA	NA	501X

Figure 4 shows the laboratory test of time required to check for 1 ounce (0.0284 kg) of non-condensable nitrogen (1% by weight) per 101 ounces (2.8633 kg) of factory charge. The total time required to check for 1% non-condensable nitrogen was 45 minutes for the condenser pressure to reach 190.6 psig (1.314 MPa) and saturation temperature to reach 98.2F or 3.2F above the 95F (36.78C or 1.78C above 35C) condenser entering outdoor air temperature. It took 10 to 25 minutes for discharge and liquid temperatures to reach equilibrium with the 95F condenser entering outdoor air temperature plus 20 more minutes for non-condensable nitrogen to coalesce in the condenser from being more dispersed throughout the system after the compressor and evaporator fan were turned off. Many technicians incorrectly assume it only takes 5 to 15 minutes to perform a standing-test of non-condensables. This is one reason why non-condensable faults are not identified.

Figure 4: Time to check for 1% Non-Condensable Nitrogen in a 3-ton non-TXV R22 Split-System with Condenser Fan Operating and Without Compressor or Evaporator Fan Operating



Refrigerant Restriction Tests

Moisture, copper particles, flux/brazing residue, and particulates left inside the system damage the compressor, clog metering devices, or make the metering device function improperly. Liquid line filter driers are recommended to remove moisture, acid, and particulates to prevent restrictions on field-charged split systems [6, 10]. **Table 13** provides laboratory test results for refrigerant restrictions on the non-TXV unit with refrigerant charge of 108 ounces or 3.06 kg. An adjustable valve on the liquid line causes a 22% increase in discharge pressure (DP) to suction pressure (SP) ratio. The impact is -30% for EER^{*}_{A}, -45% for EER^{*}_{B}, and -35% for $SEER^{*}$. Power decreased by 100 W, or 3% similar to an under-charge. The CEC RCA protocol misdiagnoses the test 701 liquid line restriction as an undercharge. Adding refrigerant charge would decrease efficiency and damage the compressor.

Table 13. Refrigerant Restriction Impacts on EER* and SEER* for non-TXV and Hot Attic

Description	EER^*_A Capacity (kBtuh)	EER^*_A	EER^*_A Impact %	EST (°F)	Delta SH (°F)	CEC RCA Protocol	EER^*_B	SEER*	SEER* Impact %	Test
Base no restriction	32,759	9.42	NA	48.1	2.1	Correct RCA	10.64	8.86	NA	189-4
Restriction non-TXV	22,385	6.62	-30%	33.51	33.3	Misdiagnosis	5.81	5.72	-35%	701

Table 14 provides test results for restrictions on the TXV unit with refrigerant charge of 102 ounces or 2.89 kg. The impact is -36% for EER^*_A, -55% for EER^*_B, and -59% for SEER*. The manufacturer RC protocol for test 801 misdiagnoses the refrigerant restriction as an overcharge. Removing refrigerant charge can cause ice formation on the evaporator coil and decrease efficiency.

Table 14. Refrigerant Restriction Impacts on EER* and SEER* for TXV and Hot Attic

Description	EER^*_A Capacity (kBtuh)	EER^*_A	EER^*_A Impact %	EST (°F)	Delta SC (°F)	Manufacturer RC Protocol	EER^*_B	SEER*	SEER* Impact %	Test
Base no restriction	32,764	9.48	NA	48.5	-2.7	Correct chg	11.14	9.21	NA	303
Restriction TXV	19,812	6.06	-36%	30.5	4.8	Misdiagnosis	5.02	3.78	-59%	801

If refrigerant restrictions are present in the system and an acid test indicates sludge, standard cleanup procedures must be followed using oversize suction and liquid line filter driers to remove sludge. Vacuum pumps are not designed to remove sludge. If a split system older than 10 years contains sludge, it might be more cost effective to install a new system with new filter drier and clean or replace the line set. Manufacturers require properly-sized liquid-line filter driers on new systems or whenever opened. This is especially important for R410A systems.[14]

Refrigerant Charge Diagnostic Tests Matrix

Accurate measurements of air conditioning models tested under laboratory conditions with single or multiple faults can be used to develop comprehensive refrigerant charge diagnostic algorithms based on DP, SP, suction temperature (ST), SH, SC, EST, COA, and liquid-line drier delta temperature (LDDT). **Table 15** provides an example refrigerant charge diagnostic test matrix [18]. Algorithms based on the matrix can be used to diagnose non-condensables, restrictions, refrigerant charge faults, condenser or evaporator heat transfer faults, low airflow, or expansion valve failure.[15] If non-condensables, restrictions or refrigerant charge faults are detected, then manufacturers recommend recovering refrigerant, removing restrictions, checking expansion valve, replacing liquid line drier (if restricted), evacuating to 500 microns (66.6 Pa) held for 20 minutes below 1000 microns (133.3 Pa), and weighing in factory charge [9, 10]. This is the most reliable method to achieve correct charge.

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[14] Filter driers must be installed on R410A systems to remove moisture from polyolester (POE) oils. R410A POE oil is very hygroscopic and quickly absorbs moisture from air which will cause acid formation. Moisture cannot be removed by 500 micron vacuums developed by evacuation pumps.

[15] If TXV failure is detected technicians should verify whether the sensing bulb is properly attached to the suction line in the correct orientation and tightly strapped with at least one copper strap and one wrap of closed-cell foam insulation with 50% overlap. Copper is 4 to 10 times more thermally conductive than brass or stainless steel.

Table 15. Refrigerant Charge Diagnostic Test Matrix

	Low ST or SH	High ST or SH
Low SC, SP or DP	Expansion valve or sensing bulb failure	Refrigerant under charge, evaporator heat transfer fault, or liquid line restriction (LDDT > 3°F), SH, SC and low EST thresholds f(OAT, SH, SC) or compressor valve failure (check compressor Watts)
High SC, SP or DP	Refrigerant over charge, condenser heat transfer fault, low airflow, or non-condensables check SH, SC and high COA thresholds f(OAT, SH, SC)	Non-condensables check SH, SC and high COA thresholds f(OAT, SH, SC) or liquid line restriction check SH, SC and low EST thresholds f(OAT, SH, SC)

Discussion

Based on 24 tests of the manufacturer refrigerant charge protocols the average accuracy was 75%. Based on 35 tests of the CEC refrigerant charge protocols the average accuracy was 74%. Based on 56 tests of the CEC temperature split protocol the average accuracy was 89%. The CEC temperature split protocol correctly diagnosed faults associated with low airflow and low cooling capacity. The manufacturer refrigerant charge protocols had problems diagnosing refrigerant overcharge faults with uninsulated TXV sensing bulb and also had problems diagnosing non-condensables and restrictions. The CEC protocol was unreliable with combined faults of low airflow and evaporator coil blockage and condenser coil blockage indicating the importance of checking and correcting obvious maintenance faults such as dirty filters or coil blockage before checking refrigerant charge and airflow. The CEC refrigerant charge protocol was unreliable diagnosing non-condensables and restrictions. For comparison, studies of medical diagnostics indicate general accuracy of 31% with 55% accuracy for easier cases and 5.8% for more difficult cases [20, 21].

Conclusions

The tested unit efficiency is within +/-3.2% of 11.2 EER and 13 SEER AHRI ratings. Hot attic test conditions with only 2% duct leakage reduce peak and seasonal efficiency by 10% to 29%. These differences are typical since current California building efficiency standards do not include component and installation differences which cause lower efficiencies. Other common installation deficiencies such as duct leakage, undercharge, low airflow, non-condensables, or refrigerant restrictions cause lower operating efficiencies. The combination of multiple faults such as low airflow, undercharge, duct leakage, and condenser coil blockage can reduce efficiency by 58% to 73%. Low airflow reduces efficiency by 3 to 12%. Tests of uninsulated TXV sensing bulb installation indicate failure to properly meter refrigerant with correct charge or over charge causing false diagnostics and reduced efficiency. Evaporator coil blockage of 50% reduces efficiency by 5 to 7%. Duct leakage reduces efficiency by 7% to 42%. Condenser coil blockage reduces efficiency by 4 to 32% and increases power use by 7 to 27%. Improper refrigerant charge reduces efficiency by 2 to 66%. Moderate non-condensables (0.3%) reduces efficiency by 13 to 19% and increases power use by 6 to 8%. Severe non-condensables (1%) reduces efficiency by 38% and increases power use by 28%. It took 45 minutes to test for 1% non-condensables for condenser saturation temperature to be at least 2C above 35C outdoor-air temperature. Liquid line refrigerant restrictions reduce efficiency by 30 to 59%. Liquid line filter driers are required to remove moisture, acid, and particulates to prevent refrigerant restrictions on field-charged split systems. Laboratory test data are used to develop methods to diagnose non-condensables, restrictions, refrigerant charge faults, condenser or evaporator heat transfer faults, low airflow, or expansion valve failure. This is not possible using generic RCA protocols specified in the California building energy efficiency standards or unit-specific manufacturer protocols. While laboratory tests of RCA faults indicate generic protocols can yield false alarms, misdetection or misdiagnosis, they were 100% accurate evaluating refrigerant charge faults when no other faults were present and 74% to 89% accurate overall. If non-condensables or restrictions are detected manufacturers recommend recovering charge, making corrections, evacuating to 500 microns (66.6 Pa), and weighing in the factory charge. This is the most reliable method to achieve correct refrigerant charge and optimal energy efficiency.

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Upgrading energy efficiency testing capacity in Turkey: Laboratory Investment, Staff Training, Testing Programme

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Abstract

Among other components such as enhancement of regulatory framework, development of market monitoring database, grant programme for energy efficiency (EE) research projects and public awareness raising, UNDP/GEF Market Transformation of Energy Efficient Appliances in Turkey Project (EE Appliances Project) executed by Turkish Ministry of Energy and Natural Resources having been in implementation in Turkey during the last 4 years also focused on improvement of appliance EE testing facilities for market surveillance purposes. At the beginning of the above-mentioned project, testing capacity was very limited for some products and there was no capacity for some other products. Therefore, this paper explains evolution of conformity assessment infrastructure in Turkey for testing of domestic appliances for compliance with eco-design and energy labeling requirements, results of appliance testing programme and how Turkey achieved a full testing capacity for domestic appliances in accordance with international laboratory standards covering the following phases:

- Laboratory inventory to establish current laboratory capacities for testing of ErPs for eco-design and energy labeling compliance;
- Investment Plan for the selected conformity assessment body based on the laboratory inventory to upgrade the existing laboratories and for construction of new laboratories where no testing capacity is available;
- Staff Training for running necessary tests under applicable eco-design implementing measures and energy labeling delegated acts;
- Appliance Testing Programme for establishing the level of compliance of the marketplace and capacity building for testing staff on testing practice;
- Accreditation as the last step for the selected conformity assessment body to be a center of excellence.

In addition to above-listed achievements, this paper will also explain ongoing success of the EE Appliances Project extending its scope to cover small domestic appliances in 2015.

Background

Efforts towards ensuring sustainability in energy, reducing dependency on imported energy commodities, mitigating the burden of energy costs on the economy and combating climate change have increased the importance of energy and using energy resources efficiently in Turkey as happened in the other countries.

Turkey aims to reduce its energy intensity by 20% up to 2023, and in order to accomplish this target, the country plans to use energy more effectively in various sectors and make contribution in minimizing the household electricity consumption and the associated greenhouse gas emissions by accelerating the market transformation of energy efficient appliances.

Turkey, because of both the EU accession process and the Customs Union with the EU, has been adopting the *Acquis Communautaire* on industrial products since 1995. In this context, the following pieces of legislation, among others[1], have been put into force in Turkey in the field of eco-design and labelling of energy related products (ErPs) since early 2000's (Table 1) [1]:

Table 1: List of EU legislation adopted by Turkey in the field of Eco-design and Labelling

Product Categories	Date of Adoption in Turkey		
	Labelling (92/75/EEC)	**Labelling (2010/30EU)**	**Eco-design (2009/125/EC)**
Framework Labelling Directive for ErPs		***December 2011***	
Framework Eco-design Directive			***October 2010***
Refrigerating Appliances	January 2010	June 2012	September 2011
Washing Machines	August 2002	June 2012	September 2011
Tumble Driers	August 2002	May 2013	July 2013
Washer Driers	August 2002		
Dishwashers	August 2002	June 2012	September 2011
Household Lighting	August 2002	-	August 2011
Domestic ovens, hobs and range hoods	February 2003	January 2015	January 2015
Air conditioners	June 2007	December 2013	July 2013
TVs		June 2012	September 2011
Vacuum Cleaners		January 2015	January 2015
Computers and Computer Servers			February 2015
Electrical lamps and luminaires		February 2015	
Directional lamps, LEDs			February 2015

As can be seen on the table above, while the labelling legislation has been in force since early 2000's, the enforcement capacity of the Ministry of Science, Industry and Technology (MoSIT) (the market surveillance authority in Turkey for the product legislation in question) was not built concurrently with the progress of adoption of the legislation, and the market surveillance activities have been limited to rare shop inspections where availability and regularity of the energy labelling practice was checked by the field inspectors only, except for occasional tests on household lamps [1]. This is mainly caused by lack of necessary testing capacity in Turkey and also insufficient training of field inspectors on enforcement of labelling and eco-design legislation as well as the market surveillance strategy and plans of MoSIT not covering this legislation to a full extent.

Particularly in the field of conformity assessment, the Turkish government notified a number of conformity assessment bodies under all product safety directives, none of which, except the Turkish Standards Institute (TSE), has capacity for energy efficiency testing of energy related products (ErPs) covered by eco-design and labelling regulations.

As far as the testing facilities of TSE is concerned, they had extremely limited testing facilities for testing of ErPs to eco-design and energy labelling regulations – even their testing staff was not properly trained and skilful in the relevant field.

Therefore, the Turkish government held prolonged consultations for longer than ten years among several governmental institutions and private sector to develop necessary testing capacity in Turkey but no concrete result was achieved as a result of those discussions.

Eventually in December 2010, the DG for Renewable Energy (DGRE)[2] under the Turkish Ministry of Energy and Natural Resources (MoENR) launched a Global Environment Facility (GEF) funded project "Market Transformation of Energy Efficient Appliances in Turkey" (EE Appliances Project) in cooperation with United Nations Development Programme (UNDP), Ministry of Science Industry and Technology

[1] Turkey adopted 26 implementing measures and delegated acts of the EU in the field of eco-design and labelling respectively by February 2015

[2] Despite its name, it is also responsible for energy efficiency activities.

(MoSIT), Turkish White Goods Manufacturers' Association (TURKBESD) and Arçelik A.Ş. in order to accelerate transformation of appliance market in Turkey towards more efficient appliances which targeted the following outcomes [1]:

- strengthening the local institutional capacity to develop, adopt and implement effective appliance EE policies;
- developing and implementing a structured compliance checking and enforcement program for appliance energy performance labels and standards;
- increasing consumer and the supply chain awareness and capacity to purchase / deliver energy efficient appliances in the Turkish market; and
- analysing and reporting the results of the project for further learning, adaptive management and, as applicable, replication in other countries.

Improvement of Regulatory Framework

As one of the initial steps, the EE Appliances Project proceeded with accelerating adoption by the Turkish government of the *Acquis Communautaire* in the field of eco-design and labelling in line with the obligations of the Turkish government under Customs Union between Turkey and the EU. As a result of this accelerating role, the EE Appliances Project achieved publication by the MoSIT of the below listed legislation in Turkish Official Gazette after publication of eco-design Directive 2009/125/EC in October 2010 and framework labelling Directive 2010/30/EU in December 2011 respectively (Table 2):

Table 2: List of legislation accelerated by EE Appliances Project

Product Category	Labelling DA	Adopted in	Eco-design IM	Adopted in
Refrigerating Appliances	(EC) 1060/2010	June 2012	(EC) 643/2009	September 2011
Washing Machines	(EC) 1061/2010	June 2012	(EC) 1015/2010	September 2011
Tumble Driers	(EC) 392/2012	May 2013	(EC) 932/2012	July 2013
Dishwashers	(EC) 1059/2010	June 2012	(EC) 1016/2010	September 2011
Air conditioners	(EC) 626/2011	December 2013	(EC) 206/2012	July 2013
TVs	(EC) 1062/2010	June 2012	(EC) 642/2009	September 2011
Domestic ovens, hobs and range hoods	(EC) 65/2014	January 2015	(EC) 66/2014	January 2015

This progress was also followed by a set of theoretical and practical (pilot shop inspections on the market) training of field inspectors as well as headquarters staff of the MoSIT as follows:

- training of 300 field inspectors on enforcement of EU eco-design and labelling regulations
- training of MoSIT headquarters staff on market surveillance programme management

However, all these training efforts were only initial steps towards establishing an effective and sound market surveillance system in Turkey without sufficient conformity assessment infrastructure in place. Therefore, in parallel to these training activities the EE Appliances project also took steps forward in view of upgrading the conformity assessment infrastructure in Turkey. For this purpose, these steps included establishment of laboratory inventory, development and implementation of laboratory investment plan, training of testing staff, development and implementation of market surveillance plan complete with product testing as detailed in the following sections.

Laboratory Inventory and Laboratory Investment

In the initial phase of the laboratory investment in Turkey, the EE Appliances Project focused on establishing the current energy efficiency testing capacity in Turkey, and for this purpose, a set of meetings was held with conformity assessment bodies (including notified bodies) in September 2012 to identify if they have necessary testing facilities for product testing according to eco-design and energy labelling regulations.

As a result of these meetings, it was assessed that only TSE had testing capacity for certain product categories – though limited – including refrigerating appliances, televisions and electric ovens. All other conformity assessment bodies operating in Turkey only focus on product safety directives.

Subsequently, the EE Appliances Project organized various visits to the laboratories of the leading manufacturers operating domestic appliance manufacturing business in Turkey (November 2011 – February 2012). These visits revealed that the manufacturers' laboratories are running at state-of-the-art technology for the product categories concerned in the EE Appliances Project. As a result, the initial state of play of eco-design and energy labelling conformity assessment was shaped out in Table 3 as follows [2]:

Table 3: Summary of EE testing capacity in Turkey as of February 2012

CABs	Product Categories				
	Cold products	**Wet Products**	**Electric Ovens**	**TVs**	**A/C**
TSE	YES-limited	NO	YES-limited	YES-limited	NO
Others	NO	NO	NO	NO	NO
Manufacturers	YES	YES	YES	YES	YES

This led the Project Management Unit (PMU) of the EE Appliances project to come up with several options to offer MoSIT as follows (Table 4) [2]:

Table 4: Options for upgrading eco-design and labelling conformity assessment infrastructure in Turkey

Option	Advantage	Disadvantage
Option 1: **Test all (future) Energy Labelling and Eco-design products in Turkey at a University or other independent site.**	Builds skill base and product knowledge in research capable centres within Turkey.	Very high (€millions) investment cost. High training and staff familiarisation cost.
Option 2: **Test all (future) Energy Labelling and Eco-design products in Turkey at TSE.**	Uses and builds testing expertise within Turkey's current testing centre.	High (€million+) investment cost (though some/all investment could possibly be made by TSE).
Option 3: **Test all (future) Energy Labelling and Eco-design products in Turkey at TSE (where TSE has facilities) and at manufacturers' laboratories in Turkey using TSE staff.**	Uses and builds testing expertise within Turkey's current testing centre, minimises investment costs.	Access to manufacturers' laboratories may be restricted and require advanced booking.
Option 4: **Test those products at TSE where they already have facilities. Test all other products at a suitably qualified laboratory elsewhere in the EU.**	No investment costs, access to a competitive market for the supply of testing services.	Minor. Need to set up suitable administrative procedure. Some difficulties associated with arranging the witnessing of testing. Note: several EU Member States use this option.

Upon review and assessment of these options by the MoSIT and DGRE, both governmental authorities decided to have those products tested at TSE where they already have facilities and other products tested at manufacturers' laboratories in Turkey and suitably qualified laboratories elsewhere in the EU

(Option 3 + Option 4) meanwhile upgrading the testing facilities of TSE to have all market surveillance tests done at TSE (Option 2) based on the following two main reasons:

- Turkish government needs a stronger and more effective market surveillance organization in the country in the field of eco-design and labelling regulations complete with upgraded testing facilities; and
- Turkish domestic appliance industry is one of the leading domestic appliance manufacturing bases in the world with its installed capacity of 25 mio. units/year ranking the first in Europe and the second in the world which seems unacceptable to Turkish government to have incomplete national testing capacity in place.

Based on this decision of the Turkish government, a laboratory investment plan has been developed under the EE Appliances Project to be implemented by TSE for upgrading its existing facilities for testing refrigerating appliances, electric ovens and televisions as well as for development of new facilities for wet products (washing machines, dishwashers and tumble driers) and air conditioners. This investment plan also covered training of the testing staff of TSE both at manufacturers' laboratories as well as external laboratories in the EU and in the form of training package in the procurement of new laboratory facilities.

Eventually in February 2013, TSE delivered to both DGRE and MoSIT their commitment to implement the laboratory investment plan for upgrading their existing facilities and for testing refrigerating appliances, electric ovens and televisions as well as for development of new facilities for wet products (washing machines, dishwashers and tumble driers) and air conditioners, ***which commitment represented a concrete step in overcoming the problem of lacking testing capacity which had been under discussion among government, industry and TSE for more than ten years with no concrete step***. This commitment also included the testing services to be rendered for the Testing Programme to be run under EE Appliances Project as detailed in the following section.

New Testing Facilities at TSE

As a result of implementation of the Laboratory Investment Plan developed under the EE Appliances Project, the following new facilities were developed by TSE:

<u>Wet Product Testing Laboratory:</u>

The laboratory accommodates 4 stations which allow 2 dishwashers or 3 washing machines to be tested at a time, or 1 dishwasher and 1 washing machine to be tested at a time or 2 tumble driers to be tested at a time according to the following harmonised European standards:

- EN 60456 - Clothes washing machines for household use - Methods for measuring the performance
- EN 50242/60436 - Electric dishwashers for household use - Methods for measuring the performance
- EN 61121 - Tumble dryers for household use – Methods for measuring the performance

Accreditation process for the laboratory is in progress and the accreditation assessment will be performed in March 2015 by Turkish Accreditation Agency (TURKAK).

Figure 1: Wet Product Testing Laboratory at TSE

<u>Air Conditioner Testing Laboratory:</u>
The newly developed laboratory is capable of testing split A/C, Water-to-Air Heat Pumps, Air-to-Water Heat Pumps, Fan Coils (wall type, ceiling type), Single-channel Portable A/C, Double-channel Portable A/C, Cassette A/C, Room A/C at rate power between 0,4 kW and 15 kW (to be upgraded to 50 kW by the end of 2015).

The following tests can be performed at the laboratory:

- EN 14511 (A/C, heat pump)
  - Identification of heating / cooling capacity
  - Identification of energy consumption
  - Identification of energy efficiency and energy efficiency rating
- TS EN 14825 (A/C, heat pump)
  - Identification of heating / cooling capacity
  - Identification of energy consumption
  - Partial load tests
  - Identification of seasonal energy efficiency and energy efficiency rating
- TS EN 1397 (Fan Coils)
  - Identification of heating / cooling capacity
  - Identification of energy consumption
  - Identification of energy efficiency and energy efficiency rating

Accreditation process for the laboratory is in progress and the accreditation assessment will be performed in March 2015 by Turkish Accreditation Agency (TURKAK).

Figure 2: Air Conditioner Testing Laboratory at TSE

Testing Programme

In parallel to the laboratory investment plan, a basic testing programme was also designed by the EE Appliances Project (considering the strict budget limitations of the project) in order to:

(a) initiate testing practice and develop testing experience at TSE;
(b) raise awareness among suppliers that their products on the market will now be subject to compliance checking complete with testing;
(c) deliver MoSIT an initial market surveillance plan for future enhancement of their annual market surveillance plans; and
(d) measure the change in compliance profile of the marketplace as a result of EE Appliance project activities.

For this purpose, a two-phase product testing programme was designed by the EE Appliances Project to be implemented in 2013 (Phase 1) and 2014 (Phase 2) in parallel to the laboratory investment plan as follows [3]:

Table 5: 2-Phase Testing Programme and Laboratory Investment Plan at TSE

Product categories	**No. of samples (2013)**	**No. of samples (2014)(*)**	**Parameters to be tested**
Refrigerating appliances	18	18	- EE rating claimed
Washing machines	18	18	- EE rating claimed - Washing efficiency - Annual water consumption
Dishwashers	18	18	- EE rating claimed - Cleaning efficiency - Annual water consumption
Electric ovens	18	18	- EE rating claimed
Televisions	18	18	- EE rating claimed - Standby/Off power consumption - On mode power consumption
Air conditioners	24	24	- EE rating claimed
TOTAL	**114**	**114**	

(*) to be revised based on 2013 test results

LABORATORY	**2013**				**2014**			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Cold products (upgraded)								
TV (upgraded)								
Electric ovens (upgraded)								
Wet products (new)								
A/C (new)								

Legend: *Upgrade/develop + training*; *Testing*

Since the total budget of the EE Appliances Project did not allow a comprehensive testing programme complete with accredited testing, inter-laboratory comparison tests, measurement of all parameters, etc. product tests were performed as single product testing focusing only on certain parameters such as EE rating claimed, annual water consumption, cleaning efficiency, etc. as shown in Table 5 above.

When selecting the samples on the market, the following strategy was followed:

- Access to as many brands and models as possible;

- Market shares;
- Country of origin;
- Claimed EE rating vs. price

In parallel to this testing programme, TSE testing staff were also provided with theoretical and practical training on product testing to applicable EN standards in cooperation with manufacturers as coordinated by Turkish White Goods Manufacturers' Association (TURKBESD), namely, Arçelik-Beko, Bosch & Siemens Home Appliances (BSH) and Vestel in accordance with the training programme outlined in Table 6 below.

The basis for developing the training plan for TSE was that whilst some of its staff may have some familiarity with some of the test procedures required, none of its staff will have the experience or expertise necessary to reach the requirements that the Accreditation Agency (TURKAK in Turkey) should require in order to accredit TSE's energy efficiency testing activities.

The generalised training roadmap provided below applied to all product types covered by the EE Appliances Project [4].

Table 6: Outline of Training Programme for TSE

Training component	Training supplier
Familiarisation training pre-TSE testing *TSE staff to spend time at test laboratory operated by TURKBESD member. TSE staff can witness testing being carried out and, possibly, can undertake the tests themselves. TSE staff can also examine the test equipment and obtain details of its specification, including contact details of suppliers.*	TURKBESD member
Advice on specification and development of TSE test facility *TURKBESD member to visit TSE to examine and comment on plans for the test facility. Member to return during development phase to examine and support the development of the facility.*	TURKBESD member
Peer examination of TSE test facility *TURKBESD member to visit TSE to examine the newly completed facility and to advise on shake-down testing and calibration.*	TURKBESD member
Training on test procedure *TSE staff to visit TURKBESD member to be fully trained to undertake the test procedure. Training programme to then continue at the TSE laboratory.* *Note: it is anticipated that TURKAK would visit TSE after this phase in order to assess the competence of the testing for accreditation purposes.*	TURKBESD member
Witness of testing at TSE / peer review of testing at TSE *Once TSE have begun to test the batch of samples supplied as part of this programme, TURKBESD member is to return to witness testing and offer further advice where necessary.*	TURKBESD member

Witness of testing at EU laboratory *Following the completion of testing the first samples at TSE, the selected 3 samples are to be tested at an accredited expert EU laboratory. TSE staff are to visit this laboratory for, if possible, an extended visit in order to witness the testing of these samples in some detail. Any differences in test results are to be examined and analysed by TSE expert staff in conjunction with the expert staff at the EU laboratory.*	EU test laboratory

Test Results

All the samples selected on the market for testing purposes, have been picked up from both brand specific stores and department stores. While selecting these samples, the labelling practice was also checked in the stores for compliance with the labelling Directive and delegated acts. Based on our observations, the degree of compliance in labelling practice was as follows:

Table 7: Degree of compliance in labelling practice by product categories

Type of Store	No. of stores visited	Refrigerating appliances	WM	DW	Electric Oven	TV	A/C
Brand specific	5	~90%	~90%	~90%	~80%	~50%	~60%
Department Store	10	~50%	~50%	~50%	~30%	~30%	~30%

As can be seen on the table above, the degree of compliance in labelling practice of brand specific stores is better when compared to that in department stores. The most common non-conformities observed in the stores include:

- Only the information strip is affixed on the electric ovens (based on former version of energy labelling directive for electric ovens)
- The label is not affixed on the product in a clearly visible manner
- The label does not have correct dimensions as required by the applicable delegated regulation
- The label is covered by a transparent plastic sheet and attached on the product by magnet pieces instead of affixing it on the product.

Acting on these observations, it can be concluded that, the relatively low degree of compliance in TVs may be due to the new delegated regulation on TVs which was recently introduced at the time when these observations were made; for electric ovens (the old version labelling was still in force at that time), the two-piece labelling practice was confusing for the shopkeepers; however, for air conditioners, no specific reason has been identified for low degree of compliance as a result of interviews with shopkeepers.

When we look at the test results for the samples picked up from the market in 2013, the degree of compliance of the products with required parameters tested is as follows:

Table 8: Test results for samples picked up from the market in 2013

PRODUCT CATEGORIES	No. of Samples	Parameters	Conforming	Non-conforming	Compliance ratio (%)
Refrigerating Appliances (*)	24	- EE rating claimed	24	0	100
Electric Ovens	18	- EE rating claimed	10	8	55.6
Televisions	18	- EE rating claimed	14	4	77.8

Washing Machines	18	- EE rating claimed - Washing efficiency - Annual water consumption	14	4	77.8
Dishwashers	18	- EE rating claimed - Cleaning efficiency - Annual water consumption	7	11	38.9
Air Conditioners	14	- EE rating claimed	2	12	16.7

(*) All cold product samples were subjected to measurement of energy consumption (e24) and measurement of volume. All samples have been found to fall within tolerances for e24 and volume values, therefore the Energy Efficiency Index (EEI) calculated was considered to meet the claimed energy efficiency rating.

Remarks, conclusions and next steps for Phase 2:

- As can be seen in Table 8 above, non-compliance concentrates rather in electric ovens and air conditioners, and it is relatively low in televisions.

- It was also identified that the non-compliance in electric ovens rather concentrates in locally manufactured electric ovens which forms significant data for the MoSIT for their future market surveillance actions.

- 2 out of 4 non-compliance washing machines did not meet the claimed energy efficiency rating and the third one had an annual water consumption out of acceptable limits and the forth one had a washing efficiency out of acceptable limits.

- On the other hand, 9 out of 18 washing machine samples had annual water consumption below the value claimed on the label Similarly, 2 washing machine samples had energy efficiency rating better than the claimed one (rated A+++ whereas claimed as A+).

- The air conditioners appear to be the product category where non-compliance is the highest. Only two samples met the claimed energy efficiency rating, and the rest were found to be far below the claimed energy classes. This was also selected by the MoSIT as another focus action for future market surveillance activities.

As a result of the first phase of the testing programme in 2013, it was decided by the MoSIT to focus more on non-complying product categories and brands in the second phase of the testing programme in 2014 and the distribution of samples to be picked up from the market in 2014 (Phase 2) is determined as follows:

Table 9: Distribution of samples for Phase 2 (revised):

Product Categories	**No. of Samples**
Refrigerating appliances(*)	28
Washing machines	21
Dishwashers	21
Electric ovens(**)	12
Televisions	11
Air conditioners	21
TOTAL	**114**

(*) Since some of the samples tested in 2013, passed the tests within tolerances, it was decided to test more brands and models.
(**) Most of the brands and models, which failed in 2013 could not be found on the market in 2014 which indicates that the manufacturers withdrawn them from the market. Therefore, some number of samples moved to TVs

Success Story – UNDP/GEF Market Transformation of Energy Efficient Appliances in Turkey

Although this paper particularly focuses on upgrading the conformity assessment infrastructure in Turkey in the field of energy efficiency (eco-design and energy labelling), Market Transformation of Energy Efficient Appliances in Turkey Project (EE Appliances Project) achieved many other successful outputs. Most of these outputs are first achievements in Turkey including:

- establishment of market monitoring database allowing to monitor energy consumption and GHG emissions caused by domestic appliances,
- training of field inspectors of MoSIT,
- public awareness raising campaigns,
- training of sales staff, and
- the grant programme for research projects in 5 Turkish universities which also led to opening of new must and elective courses on energy efficiency in domestic appliances.

For all these achievements, the EE Appliances Project has been selected as a success story among GEF projects regionally in 2013 and globally in 2014, and eventually granted time extension for one year until December 2015 upon proposal by the PMU to the GEF Secretariat for extension of scope in 2015 to cover energy efficiency in small domestic appliances and monitoring of energy consumption in households caused by selected appliances.

Conclusions

The laboratory investment, complete with upgrading of existing laboratories, establishment of new laboratories and staff training, has been an enormous step in Turkey for strengthening the conformity assessment infrastructure in the field of energy efficiency of ErPs. It represented a concrete step in overcoming the problem of lacking testing capacity which had been under discussion among government, industry and TSE for more than ten years with no concrete step.

In addition, although being very simple due to budgetary limitations, the market surveillance programme complete with product testing in parallel to laboratory investment suited several needs of both MoSIT and TSE by building capacity for market surveillance activities of MoSIT and testing practice of TSE testing staff. It also raised awareness among suppliers that their products on the market will now be subject to compliance checking complete with testing.

Furthermore, the market surveillance programme complete with product testing developed and implemented under EE Appliances Project is the first in Turkey and MoSIT merged the strategies and outcomes of this programme in to their market surveillance strategy and annual market surveillance plans, and this fact ensured sustainability of results of EE Appliances Project.

Last but not the least, the product testing issues in the field of energy efficiency became a significant discussion topic among government, conformity assessment bodies and product suppliers.

As a result, the EE Appliances Project is still stepping forward with its striking achievements and expected to achieve further with its extended scope with small domestic appliances in 2015.

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Novel challenges in standardization of household appliances

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Abstract

CENELEC TC 59X 'Performance of household and similar electrical appliances' is very active in preparing European Standards in the context of the EU energy labelling scheme and ecodesign requirements. This concerns improving the present product standards on measurement of performance criteria and creating new ones along the standardization requests (or 'mandates') from the European Commission.

Besides the usual parameters (e.g. energy consumption, water consumption, noise) there is a new focus on other elements as well. One of these is the test procedure for durability criteria for vacuum cleaners. There are also other challenges like the clear definition and naming of processes like the "eco" standard programme for dishwashers or the description how to inform about the dismantling of appliances (new request out of a draft standardization request on water heaters). New work items are dedicated to commercial appliances as well.

Due to new activities from the European Commission on setting clear requirements on technical documentations there is increasing interest in the issue of uncertainties and on how to set tolerances. CLC/TC 59X/WG 16 dealing with uncertainties has already developed an approach which is put into the debate now.

Furthermore there is more work to be done with respect to solving the problem on the need to have repeatable and reproducible measurement procedures and the intention of the Europen Commission to regulate parameters, which are not accurately measureable (like the new material efficiency parameters).

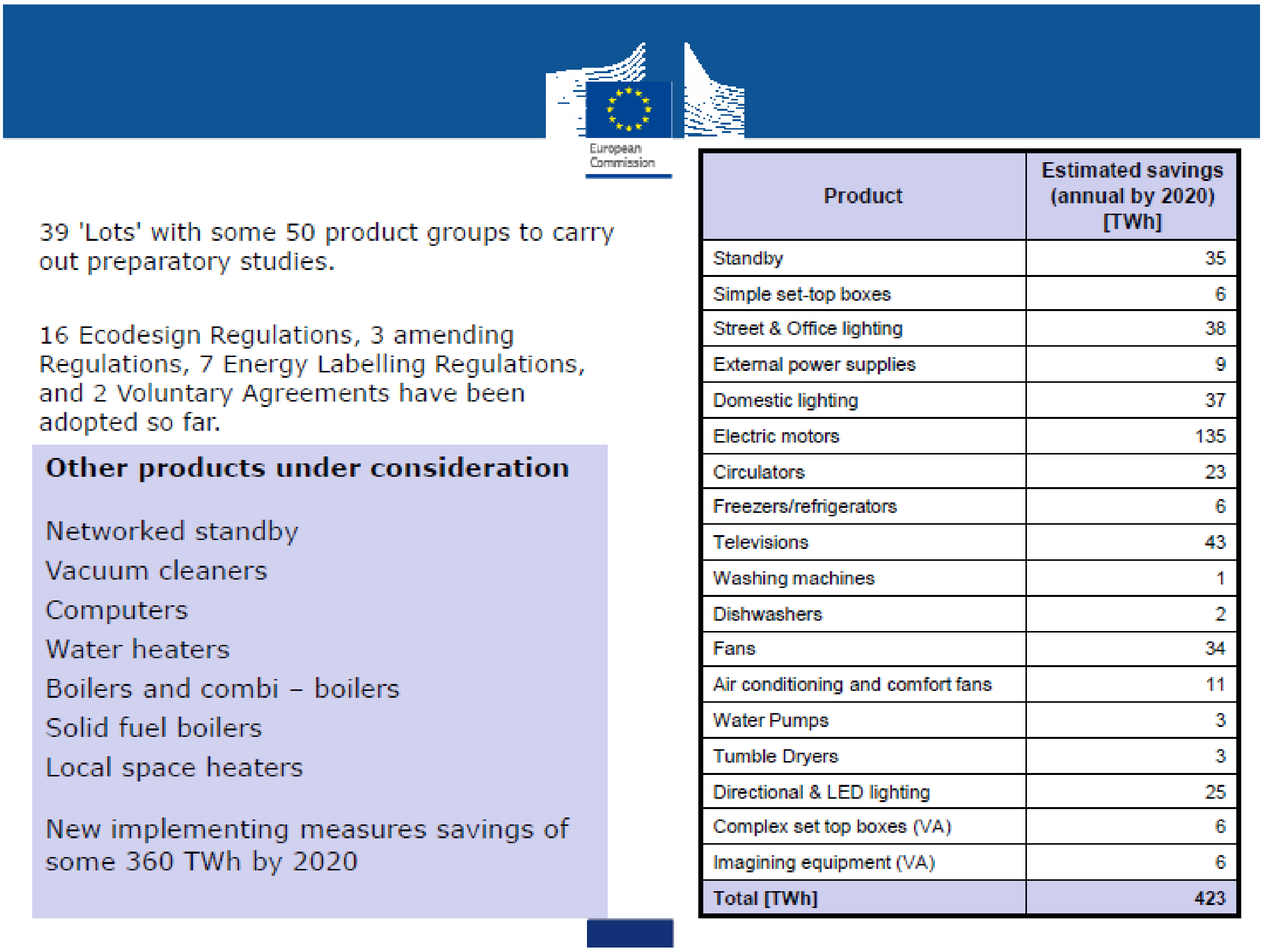
This paper is reviewing the various activities of standardization in the context of the energy labelling scheme and ecodesign requirements. New developments and challenges are also illustrated.

1. Introduction

Regulatory instruments and labelling systems are meanwhile adopted for various product categories. This can be seen as the success of the pioneering work done in the field of household appliances. Ten years ago there used to be requirements and labelling systems for some products, like refrigerators or washing machines, only.

Nowadays there are measures for many product categories in place as well, like vacuum cleaners. Beyond household appliances there are measurements established also. Amongst these newcomers there are TVs, motors, pumps and the horizontal measures for standby and external power supplies [11]. The experience from the area of household appliances gathered in the past is very valuable. Twenty years experience of CLC/TC 59X ‘Performance of household and similar electrical appliances’ [1] is well recognized by the other Technical Committees.

Standards do create and stimulate innovation and competition. Standardization also contributes to the savings in energy consumption. Indeed huge energy savings across Europe are projected. They are estimated to be about 800 TWh/year [2], equivalent 400 MtCO_2/year in 2020 (including product under consideration). This rather high overall amount could be questioned. However, for the portion of household appliances related to CLC/TC 59X a saving between 20 and 30 TWh/year seems to be a realistic figure.



Product	Estimated savings (annual by 2020) [TWh]
Standby	35
Simple set-top boxes	6
Street & Office lighting	38
External power supplies	9
Domestic lighting	37
Electric motors	135
Circulators	23
Freezers/refrigerators	6
Televisions	43
Washing machines	1
Dishwashers	2
Fans	34
Air conditioning and comfort fans	11
Water Pumps	3
Tumble Dryers	3
Directional & LED lighting	25
Complex set top boxes (VA)	6
Imagining equipment (VA)	6
Total [TWh]	**423**

Figure 1: Energy savings; calculated by the European Commission, 2013, [2].

Even more attention to energy savings is necessary [2]. According to CLC/TC 59X this concerns the standardization process itself and the integration of new issues. The most challenging tasks at the moment are:

- definition and implementation of procedures that allow publication of standards in a shorter timeframe,
- integration of uncertainties; and

- integration of new parameters and aspects like interconnectivity, durability, resource efficiency.

2. Mission of CLC/TC 59X

CENELEC (European Committee for Electrotechnical Standardization) is the European standardization organization on electrotechnical matters. Household appliances are covered under CLC/TC 59X [1]. CLC/TC 59X is one of the biggest Technical Committees in CENELEC. It is structured in Working Groups. In the last three years, many of them have been established to meet the growing number of regulatory projects of the European Commission. This also applies to commercial appliances that were covered by the standards only sparsely so far.

In total, CLC/TC 59X currently consists of 19 Working Groups. Moreover, some Working Groups also have Subgroups to meet the requests adequately. See Table 1 below. Additionally there is a Joint Working Group with CLC/TC 100X on standby.

WG 01	Washing machines and tumble dryers
WG 01-01	Long term effect of new detergent
WG 01-02	Draft program for the main test new detergent RRT 2004 EN 60456 2nd ed.
WG 01-05	Wrinkling assessment
WG 01-06	Future standard
WG 01-07	Spinning efficiency and accuracy
WG 01-08	Rinsing performance
WG 01-09	Dryer
WG 01-10	Dosage of detergent
WG 01-11	Washer-dryers
WG 01-12	Commercial laundry machines
WG 02	Dishwashers
WG 02-01	Commercial dishwashers
WG 04	Water heaters
WG 05	Induction cooking
WG 06	Surface cleaning appliances
WG 06-01	Water filter vacuum cleaners
WG 06-02	Uncertainties for vacuum cleaners
WG 07	Smart household appliances
WG 08	Performance of electrical household and similar cooling and freezing appliances
WG 09	Microwave cooking appliances
WG 10	Surface cooking appliances
WG 11	Power consumption of vending machines
WG 12	Electric room heating appliances
WG 13	Ventilation hoods
WG 14	Measurement of noise emission
WG 15	Coffee makers
WG 16	Uncertainties and Tolerances
WG 17	Ovens (Hobs excluded)
WG 18	Electric ovens for commercial use
WG 19	Comfort fans
WG 20	Commercial refrigerating appliances for use in commercial kitchens

Table 1: Working Groups and Subgroups of CLC/TC 59X, [1].

The objective of CLC/TC 59X is 'to prepare European Standards on methods of measurement of characteristics which are of importance to determine the performance of household and similar electrical appliances and are of interest to the consumers' (scope of CLC/TC 59X, see [1]). Thus the focus is on the energy consumption, water consumption, product related performance parameters, noise, etc.

3. Recent developments and challenges

The implementing measure on vacuum cleaners sets out minimum requirements on durability of the motor and the hose, see [3]. Here the European Standard EN 60312-1 from CLC/TC 59X is providing a test procedure accordingly. However, this must be updated to some extent along a forthcoming standardization request [4].

Along these requirements for vacuum cleaners a discussion was started recently on a more general approach on establishing durability and resource efficiency requirements integrated in ecodesign implementing measures on a broader scale. However, the draft standardization request from the European Commission on this was not agreed by the European Standardization Organizations CENELEC and CEN as the document was deemed not mature enough to enable proper standardization. A second draft is presently under discussion [5]. In the Task Force 4 'Resource efficiency' of the CEN-CENELEC Ecodesign Coordination Group new activities have been started. It is very important to see what would be finally the mission for the product-related Technical Committees in CENELEC and CEN and how to organize the work to be done and to cooperate with each other. It will be a big challenge, as at the moment CLC/TC 59X is simply not prepared to start standardization of durability and resource efficiency items straight away.

Besides preparing measurement procedures, standardization recently had the task to define a common name for a uniform identification of a 'standard programme', [6]. The CLC/TC 59X Working Group on dishwashers has introduced the naming of 'eco' which has been meanwhile harmonized by the EU Commission. A similar point to this is the standardization request from the European Commission on a description of disassembly of appliances [7].

Variability and measurement uncertainty are underpinning the standards. The issue became momentum in the last two years as a result of the success of the regulations on labelling and ecodesign it was necessary preparing more precise test methods. New products, such as vacuum cleaners entered into the arena also. On the other hand experiences from market surveillance activities and also experiences from the market itself had led to specific requests from EU Commission and Member States and stakeholder working on transparent approaches and improving the test methods. With this respect the fundamental importance of round robin testing towards is well acknowledged.

4. Legislative process

The utmost essential part of standardization work of CLC/TC 59X is dedicated to harmonized standards. Which means: '*A harmonised standard is a European standard elaborated on the basis of a request from the European Commission to a recognised European Standardisation Organisation to develop a European Standard that provides solutions for compliance with a legal provision. Such a request provides guidelines which requested standards must respect to meet the essential requirements or other provisions of relevant European Union harmonisation legislation..'* [8]. A 'request', means 'standardization request', or simply 'mandate'.

Mandates from the European Commission are thus prerequisite for harmonized standards. And mandates are always related to certain regulations. For CLC/TC 59X this are the regulations on labelling and on ecodesign which supplement Directive 2010/30/EU on energy labelling [9] and implement Directive 2009/125/EC on ecodesign [10]. An overview of existing regulations is given in [11].

It must be kept in mind that the standards are usually prepared by IEC/TC 59 (International Electrotechnical Commission) in order to guarantee coherence on global scale. They are subject to parallel voting in IEC and CENELEC according to the Dresden Agreement [12]. In addition common modifications often need to be integrated into the European version of the standard so as to align the document with the EU Regulations.

For proper referencing of the European Standards in the OJEU (*Official Journal of the European Union*) each harmonized standard has to contain an Annex ZZ, which establishes the link between the clauses of the standard and the requirements of the regulations they aim to cover.

Standardization must be aware of what the legislative process is. Figure 2 shows what the phases and steps are in the process of preparing the regulations supplementing the labelling Directive 2010/30/EU [9] and the regulations implementing the ecodesign Directive 2009/125/EC [10].

It seems to be almost quite comfortable to prepare standards right in time because of a rather long legislative process of more than 4 years time. However, starting a new standardization project right in time at step 1 of the legislative process is not possible and it is even not possible to start somewhat later. This is because it is not clear in this early stage what should be standardized at all. Therefore official mandates from the European Commission are normally to be expected right after the publication of the respective regulation.

An overview of existing standardization requests from the European Commission can be found on the EC's website [8].

5. Standardization Process

When to start the standardization work?

This is a simple question. However, it cannot be answered easily because there are many factors. For sure, the hard work can begin after the definition of the objective only. And this is in fact depending on two things. The first one is the publication of the regulation. For specialists this is the date where the Regulatory Committee has made its final decisions which are some months ahead of the date of the publication of the regulation. Secondly: The acceptance of the mandate by CENELEC and/or CEN is the ultimate point from which on the standardization work can start.

The relationship between regulation and standardization regarding the ecodesign (and labelling as well) is explained in the mandate M/495 from the European Commission, the so-called horizontal mandate [13]. Table 2 gives a good overview about what is meant. From this figure the standardization shall start right after the voting in the Regulatory Committee and after receiving the technical update of Annex B to M/495, which is the actual 'mandate' in which concrete technical requests are prescribed.

However, this understanding is no longer fully valid. With the entry into force of the Regulation 1025/2012 on European standardisation on 1 January 2012, the concept of horizontality of M/495 lost its legal validity. M/495 is therefore no longer used for triggering new standardization work. This means that individual mandates have to be issued (instead of technical updates of Annex B). This effectively needs some more time. So, although Table 2 is not valid entirely, it gives an overview about the process. The starting of the standardization work is normally after the formal acceptance of a regular mandate, which is normally some months after the publication of the regulation (earliest).

For sure, something can be done proactively at earlier stages in the legislative process. Table 2 shows standardization should do some pre-work already in the preparatory study phase. This should include gap analysis, for example. Indeed that is what Technical Committees can do in order to be well prepared for the execution of the standardization request in due time or even shorter timeframe.

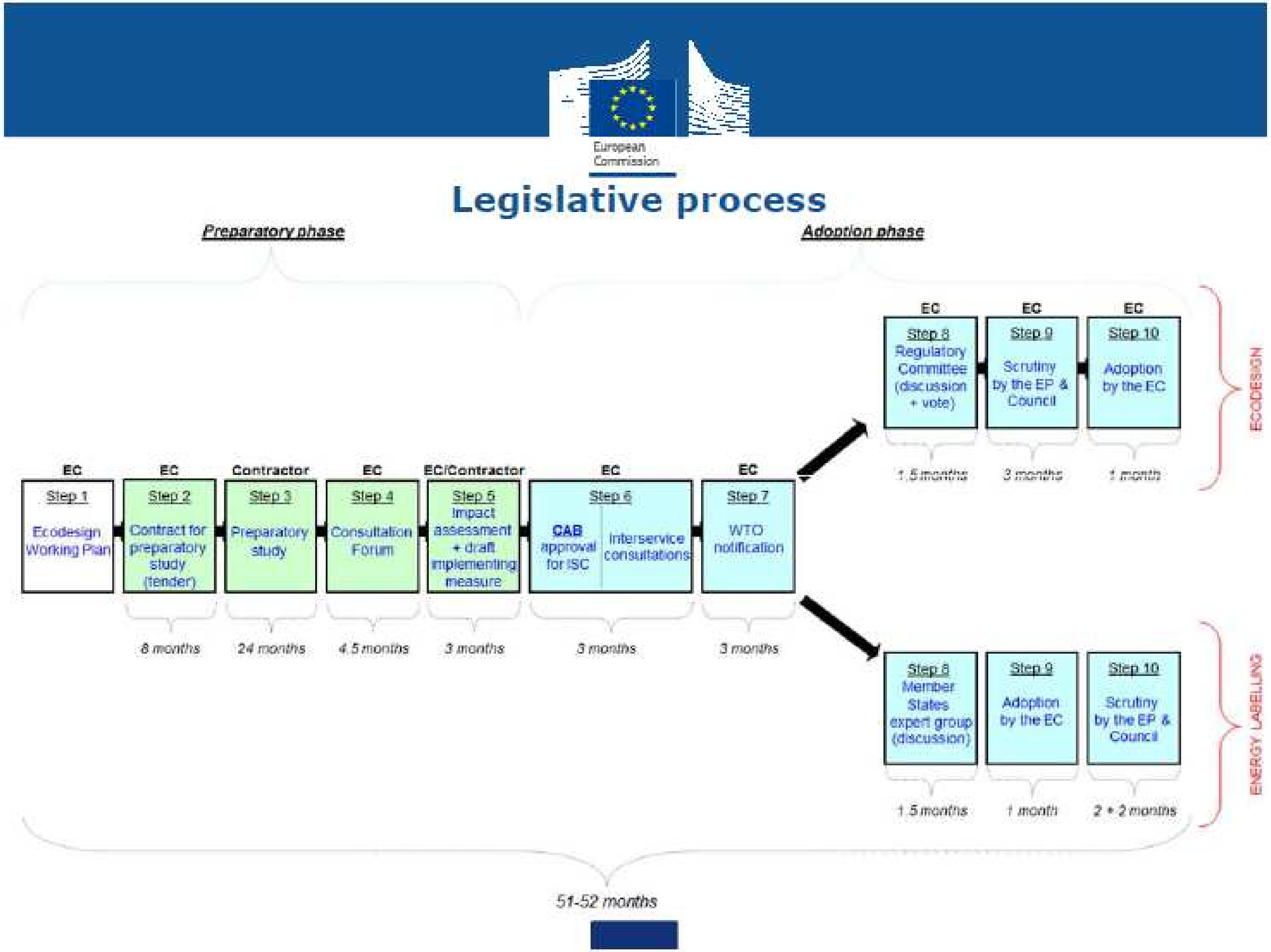


Figure 2: Legislative process for EU implementing measures on ecodesign and delegated regulations on labelling. From EU Commission, 2013, [2].

Standardization requests from the European Commission

In order to avoid stalling situations later on the questions on what shall / should / could be standardized in short / mid / long term, the persons involved in standardization should be involved adequately and in an early stage of the workflow of preparation of the respective mandate (standardization request) already. Technical Committees should be involved at the stage 2 ‘Drafting work’ (Figure 3) in order to avoid conflicts and lose time.

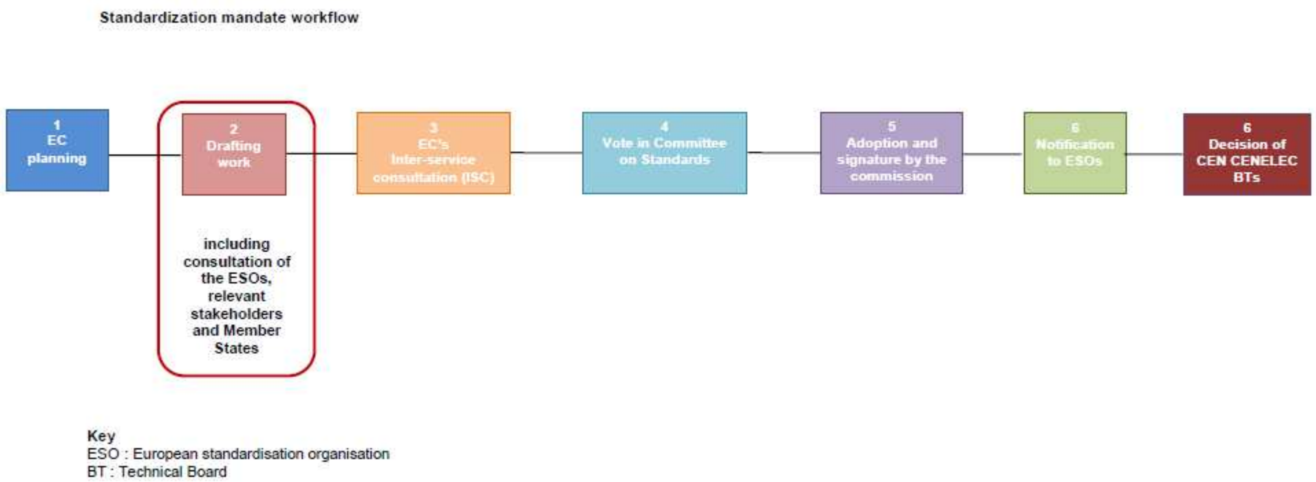


Fig. 3: Standardization mandate workflow, [16].

Harmonization

References of harmonized European Standards (hENs) are finally published by the European Commission in the *Official Journal of the European Union*, OJEU (see Table 2). Member States' Authorities should consider these standards as relevant when making verifications. On the other side they are used to provide presumption of conformity for the manufacturers and importers insofar as they do apply the respective hENs (see example of vacuum cleaners in [14]).

Table 2 shows that first requirements of regulation on ecodesign and labelling are normally going to be applied approximately 12 months after they have been published. This gives time to the manufacturers and importers for the implementation.

Ideally harmonization should take place before the ‘application’ of the regulation (see Table 2). Often this is not possible. And even mandates set longer timeframes (than 12 months). In such situation it is possible for the European Commission to publish in the OJEU Transitional Methods for Measurement and Calculations (see [9], [10]; example is given in [15]). The European Commission appreciates support from Technical Committees of CEN and CENELEC as the elaboration of these requires technical knowledge and experience in testing. The work on these Transitional Methods is often very beneficial for executing the mandate. Thus it is recommended to Technical Committees organizing internal work to well in advance in order to prevent conflicting situations and or double work.

Timeframe for the preparation of standards in relation to Ecodesign implementing measures

Table 1 – Typical timeline for developing new implementing measures and corresponding deadlines for adopting standards								
Implementing Regulation	Ecodesign preparatory study		Preparation of proposal (Commission)	Discussion with Consultation Forum	Vote in Committee and EP scrutiny	Formal adoption (OJEU)		Appli cation
Indicative timeline	**24 months**		**6 months**	**6 months**	**6 months**	**6 months**	**12 months**	
Related Standards (**'at the latest' deadlines**)	Definition of the scope of the study & identification of main standardisation gaps	End of study : First agreement on the product definition and categorisation, and standardisation needs	CEN CENELEC: adoption of preliminary work items		Update of Annex B CEN CENELEC: final adoption of work items		Publication of the EN standard(s) in OJEU	

Table 2: Ideal timeframe for the preparation of standards according to mandate M/495 from the European Commission [13].

Coordination by CEN-CENELEC Ecodesign Coordination Group

Pioneering work in standardization on energy efficiency was done in the past to a great extent by CLC/TC 59X. As now labelling and ecodesign is much broader [9], [10] cooperation amongst Technical Committees is desired.

The CEN-CENELEC Ecodesign Coordination Group (Eco-CG) was established in 2012 as a joint Group for coordinating and supporting the work to be done by the Technical Committees. This CEN-CENELEC Ecodesign Coordination Group is also the bridge to the European Commission and stakeholders. CLC/TC 59X is very active in this Group and its Task Forces.

About 30 Technical Committees in CEN and CENELEC and a number of standardization stakeholders are under the umbrella of the CEN-CENELEC Ecodesign Coordination Group right now. The group includes also EC representatives. It is chaired by Mr Martial Patra (France) and its Secretariat is held by AFNOR, the French Standardization Committee.

Amongst other topics the CEN-CENELEC Ecodesign Coordination Group is presently dealing with coordinative work across the various Technical Committees.

New topics came across also recently on noise testing, networked standby, durability and resource efficiency (see above) and the question on how to deal with uncertainties and tolerances in standards and regulations.

Special issue - Uncertainties and tolerances

EU Regulations on ecodesign and labelling [11] define hard limits, class widths, and values to be declared. For each parameter there are tolerances levels set out in these regulations. Measurement uncertainties are unavoidable. Technical Committees are necessarily asked to be aware of and to develop strategies for reduction. Here CLC/TC 59X/WG 16 'Uncertainties' is preparing guidance for the various Working Groups in order to follow a common approach. One main item is performing standardized round robin tests from which uncertainties levels can be derived. In a Technical Report from CLC/TC 59X [17] the procedure on how to conduct round robin tests is described. This Technical Report makes round robin testing as a part of standard development and maintenance. It is the first time round robin testing is defined in a consistent manner. It provides guidance for all the concerned partners in the process which are the contracting body, the coordinator and the collaborators. The result of round robin testing, namely the values of repeatability and reproducibility, is to be reported in a clear format.

Tolerances are set by regulators. But, what are the technicalities behind? Here CLC/TC 59X/WG 16 is active in supporting regulators. Recently a document was handed over to regulators and stakeholders [18]. In short: Round robin tests shall be made in a standardized way. 'Expanded uncertainties' are to be calculated. *'Setting the tolerances close to the expanded uncertainty is a fair compromise which takes into account uncertainty of measurement whilst restricting the room for making misleading declarations'* [18].

Moreover CLC/TC 59X/WG 16 is discussing very deeply on how to proceed when it comes to uncertainties in real measurements. An internal Guide was recently published [18]. This gives guidance to standard developers of CLC/TC 59X on how to report uncertainties in their product specific standards. This internal guide was a valuable input for the CEN-CENELEC Ecodesign Coordination Group's Task Force 2 'Uncertainties and tolerances' as well. This Task Force recently prepard a draft document called 'Guide to assess measurement uncertainties for products and services under the ecodesign Directive' [20]. It is the intention to implement this guide in the various Technical Committees and legislative activities as well.

6. Outlook

CLC/TC 59X is continuing dynamically preparing standards related to ecodesign and energy labelling. To keep strict time schedule it is desired to get involved in early stage. Experts must be involved in the preparatory studies of the regulations and in the early phase of the workflow of the mandates.

Achievements have been attained for understanding the integration of uncertainties in the standards. However, uncertainties and the tolerance issue are remaining main subjects. In this context even more focus must be on round robin testing.

CLC/TC 59X already started actively working on commercial appliances and will continue.

It is not clear at the moment how new criteria like resource efficiency and durability will affect future work. CLC/TC 59X will follow up the new developments closely, namely the activities concerning the upcoming mandate.

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The evolution of the certification of Heat Pumps

Arnaud Lacourt

EUROVENT CERTITA CERTIFICATION

In a European context where current and future regulations, such as those related to Eco-design, are essentially based on a self-declaration of product performance by the manufacturers themselves, voluntary certification provides reliable product data and helps organize the market. Transparency and availability of certified performance is also a very effective tool to promote the emergence of products and ever more effective technical solutions. Either directly when certification standards introduce performance thresholds or indirectly by the only competition. As an example, over the years we observed a steady increase in COP values of heat pumps certified.

Being aligned with market expectations also means anticipating future developments to support industrials and the evolution HVAC-R market. One example of this mutation is the Eco-design regulation that will dramatically shake up the current situation.

In a complex environment where the French thermal regulation for building, RT2012, adds to various EU regulations, third-party certification is key to help highlight energy efficient heat pumps providing acceptable acoustic performance.

Since 2013, the brands "Eurovent Certified Performance", "NF PAC - Heat Pumps" and "Multi-NF Energy" are issued by a single certification body Eurovent Certita certification.
These brands have a strong market recognition either as French, European or Global certification. They cover different types of heat pumps, each having its own scope and characteristics.

In this presentation, as we will see in further details the evolution of these certification marks, including the introduction of seasonal performances and the European Eco-label.

DEVELOPMENT OF HEAT PUMP SYSTEM CERTIFICATION

The main Certification Contributors

In a European context where current or future regulations, such as those on eco-design, are effectively based on the declaration of product performance by the manufacturers themselves, voluntary certification provides reliable product data, and helps organise the market.

The publication of certified performance by an independent and accredited body ensures that the design offices, installers, and users in general have a consistent, reliable, and continuously up -o-date database at their disposable, and manufacturers to enhance the best features of their products.

In a highly competitive market, product certification plays a key role in ensuring fair trade and establishing trust between operators.

In addition, transparency and availability of certified performance constitutes a very effective tool in promoting new product development and ever more effective technical solutions. Either directly when the certification standards introduce performance thresholds, or only indirectly through free competition. Over the years, it was possible to observe a steady increase in COP values for certified heat pumps.

Finally, it should be noted that certifications, such as those granted by Eurovent Certita Certifications, are developed closely with the professional sectors involved, which ensures consistency with market expectations and developments. Examples include the introduction, in consultation with AFPAC, in the size certified characteristics and the acoustic specifications relating to heat pump noise. Researching consistency with market expectations also signifies anticipating future developments in support of manufacturer and industrial developments. In particular, this is what is implemented in the NF PAC and Eurovent Certified Performance certifications, as the application of Eco-design regulations will dramatically shake up the current situation.

Since 2013, the trademarks "Eurovent Certified Performance" (Figure 1), "NF PAC - Heat Pumps" (Figure 2) and "NF Multi-Energies" (Figure 3) have been issued by a single certification body: "Eurovent Certita Certification" [1, 2]. These trademarks, which have an impact on French and European level and are also globally renowned, cover all types of heat pumps in their various functions, a scope which is described later in this document. In a complex context, where the thermal regulation of buildings RT2012 [3] specific to France, in addition to regulations on marketing products with European texts that are gradually being written, certification will showcase in a more understandable manner energy efficient products to prescribers and final users, products which have an acceptable acoustic performance. The development of this trademark certification is presented below.

Figure 1:
ECP trademark

Figure 2:
NF PAC trademark

Figure 3:
NF Multi-energy trademark

1. Current status of heat pump certification

October 2014, marked the 20th anniversary of Eurovent Certification activities. On the other hand NF exceeded its thousandth heat pump certification, and a new reference document appendix for the Multi-energy standard dedicated to hybrid systems is available, which combines heat pumps and boilers. On this occasion we can review the road we have gone down and the status on the current type and number of certified reference documents. (Table 1).

Table 1: Distribution of Certified Products (June 2014)

Type of Heat Pump	NF Heat Pump	Eurovent Certified Performance
Air/air	/	2835
Air/Water	1845	10417 of which 1512 x 100 kW
Water/Water	258	3068 of which 560 x 100 kW
Glycol Water/Water	471	/
Sanitary Hot Water	192	/
Swimming Pool	34	/
Gas	6	/
Variable Refrigerant Flow	/	20

Faced with market statistics available from Eurovent Market Intelligence and Clim'Info, this data support the assertion that the coverage of certified Heat Pumps on the European market is very high.

2. From “Standard” performance to “Seasonal” performance

Energy performance characterisation for eat pumps is gradually migrating from EER and COP nominal performance EN 14511 [4]) to seasonal performance (EN 14825 [5]), whose recent developments, and those to come, will cover more and more types of products.

Whilst the industry has implemented ESEER (European Sesonal Efficiency Ratio), certified since 2007, recently published regulations or those in the process of being published talk about seasonal coefficient of performance (SCOP) in heating mode, and its equivalents SEER and SEPR in cooling mode (see Table 2).

In order to compare the heating solutions between different technologies, the seasonal effectiveness is defined in primary energy etas (η_s). In order to respond to these developments, Eurovent Certita suggests that manufactures certify this new performance. Since the 2013 revision of the reference document "AC1" (Air Conditioners ≤ 12 kW - Luxury Air Conditioning Units), manufacturers are required to declare the SEER, covered by eco-design 206/2012 [6] and labelling 626/2011 [7] regulations. Products which do not fall within the thresholds of the regulation are excluded. Since revision 8 of the reference document NF PAC published in the autumn of 2014, manufacturers can certify SCOP and seasonal energy efficiency for the heating premises η_s, covered by regulations 813/2013 [8] 811/2013 [9], as an option. Since the 2015 revision of the reference document LCP-HP (Liquid chilling packages and heat pumps), published December 2014, manufacturers are required to declare the SCOP and η_s, data that will be published in the autumn of 2015.

In the 2016 or 2017 revision of the reference documents AC2, AC3 (Air-Condition Units<=100 kW) and RT (Rooftop Units), manufacturers shall declare the SCOP, SEER and/or the etas, knowing that the regulation was passed in April 2014 but the unreleased documents have not been published in the official EU journal yet, and the mandate to meet the harmonised standards on the needs and regulatory testing methods is in its early stages.

3. Sanitary Hot Water

Present in the source document NF PAC since August 2012, the certification of dual service heat pumps producing hot sanitary water evolved in its 7th revision, which was published at the end of June 2014 to ensure the further certification of heat pumps and storage tanks with a reference simulation tool.

Regarding future developments, a work group has been meeting since September 2014 to introduce by the summer of 2015, the possibility of certifying collective sanitary hot water, with or without the 2000L capacity limit.

4. A European Heat Pump Certification program: “Euro Heat Pumps”

The European Heat Pump Certification program: “Euro Heat Pumps” is a bridge between the NF programme and the ECP trademark. The first certificates shall be distributed at the beginning of 2015 and the data shall be available online at the end of winter.

5. Multi-Energy Systems

Concerning the NF Multi-Systems trademark, it does not concern the enhancement of each component, but the enhancement of the system’s performance as a whole.

The first appendix of the multi-energy reference document is dedicated to hybrid heat pumps (hybrid heaters). In this case specifically, it concerns the enhancement of the performance regulation system that can be optimised in such a way so as to use fossil fuels or electricity in the most favourable conditions during the key operating points of the product. It can also be for consumers using electricity during off-peak rather than peak periods

The first certificate was published in November 2015. The trademark committee also addressed it in 2014 to introduce seasonal performance in certified data in 2015 or 2016, while the taking into account these systems in the EN 14825 standard has not been resolved in the next version of the standard, but is in the process of being defined in the following version.

Table 2: Summary Term Table (in English) and the principal equations on the seasonal performance characterisation of Heat Pumps

Terms	Cooling mode	Heating mode	unit
reference design conditions reference temperature conditions cooling mode: 35 ºC dry bulb (24 ºC wet bulb) outdoor and 27 ºC dry bulb (19 ºC wet bulb) indoor heating: for average:-10°C, colder : -22°C and warmer: +2°C climates	$T_{designc}$	$T_{designh}$	°C
load or demand load of the building at certain temperature conditions	P_c	P_h	kW
full load load at reference design conditions	$P_{designc}$	$P_{designh}$	kW
part load ratio load divided by the full load	PLR		%
capacity capacity a unit can deliver at certain conditions	DC		
capacity ratio load divided by the declared capacity	CR		
bin hours duration at a given temperature for a specific location	h_j		h
bivalent temperature (CR=100%) lowest outdoor temperature where capacity is equal to the load		$T_{bivalent}$	°C
operation limit temperature lowest outdoor temperature where the unit still delivers capacity		T_{OL}	°C
reference annual demand(s) representative annual demand(s)	Q_c	Q_h	kWh
efficiency (energy efficiency ratio and coefficient of performance) capacity divided by the effective power input at standard conditions: at conditions of EN 14511	EER	COP	kW/ kW
at part load: at conditions of EN 14825 (degraded for fixed stage units)	EER_j	COP_j	
electric back up heater (below Tbivalent) supplementary electric heater, with a COP of 1		elbu	kW
thermostat off corresponding to the hours with no load	TO		
standby unit partially switched off but reactivable by a control device or timer	sb		
off unit completely switched off	off		
crankcase heater (to limit refrigerant concentration in oil at compressor start) where a crankcase heater is activated	CK		
auxiliary power consumptions $\sum h_{aux}.P_{aux} = h_{TO}.P_{TO} + h_{sb}.P_{sb} + h_{CK}.P_{CK} + h_{off}.P_{off}$	TO, sb, off, ck		kWh
degradation coefficient for fixed stage units (same equations for COPj) efficiency loss due to the cycling of respectively chillers and ACs $EER_j = EER.\frac{CR}{c_c.CR+(1-c_c)}$; $EER_j = EER.\left(1 - C_d.(1-CR)\right)$ = *EER.(Part Load Factor)*	Cc / Cd		% kW/ kW
reference seasonal efficiency [reference: EN 14825, 2013] seasonal efficiency calculated for the reference annual demand $SEER = \frac{Q_c}{\frac{Q_c}{\frac{\sum h_j.P_{c,j}}{\sum h_j.\left(\frac{P_{c,j}}{EER_j}\right)}}+\sum h_{aux}.P_{aux}}$; $SCOP = \frac{Q_h}{\frac{Q_h}{\frac{\sum h_j.P_{h,j}}{\sum h_j.\left(\frac{P_{h,j}-elbu_j}{COP_j}+elbu_j\right)}}+\sum h_{aux}.P_{aux}}$	SEER	SCOP	kWh/kWh
active seasonal efficiency seasonal efficiency excluding auxiliary consumptions	$SEER_{on}$	$SCOP_{on}$	kWh/ kWh
European seasonal energy efficiency ratio [reference: Eurovent Certification, 2008] Antecedent term used for SEER before European standard was issued *ESEER* $=0.03.EER_{100\%}+0.33.EER_{75\%}+0.41.EER_{50\%}+0.23.EER_{25\%}$	ESEER	-	kWh/ kWh
integrated part load value [reference AHRI, 1998] (EER in kW/Ton) First equivalent to ESEER, with weighting coefficients related to the United States *IPLV* $= 0.01.EER_{100\%}+0.42.EER_{75\%}+0.45.EER_{50\%}+0.12.EER_{25\%}$	IPLV	-	kW/ Ton

6. European Eco-Label

To promote the most environmentally friendly products, the Eco-Label Directive [10] completes the eco-design and labelling guidelines. For heat pumps, the criterion for the attribution of the co-label, initially published 9 November 2007 [11] and valid until 31 October 2014, were updated by the decision of the committee' dated 28 May 2014 [12]. Note that the eco-label had been attributed to a handful of product lines in France, Belgium and Germany.

An extension of the scope of the text on hybrid devices is amongst the latest advances, including the emergence of a Total Equivalent Warming Impact (TEWI), based on the Global Warming Potential (GWP) of the refrigerant used with conventional end-of-life leakage rate fixed at 35% and the seasonal energy effectiveness for the heating of premises η_s.

Conclusion

In a changing regulatory and normative context, the offer of certification by Eurovent Certita Certification may be adapted to the heat pump market, therefore ensuring a guarantee to the final client a better understanding of performance thanks to the collaborative work including all stakeholders, while covering as extensively as possible existing solutions and technologies.

References

[1] www.eurovent-certification.com

[2] www.certita.org

[3] http://www.rt-batiment.fr/

[4] EN 14511 - Air conditioners, liquid chilling packages and heat pumps with electrically driven compressors for space heating and cooling

[5] EN 14825 - Air conditioners, liquid chilling packages and heat pumps, with electrically driven compressors for space heating and cooling - Testing and rating at part load conditions and calculation of seasonal performance

[6] Commission regulation (EU) No 206/2012 of 6 March 2012 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for air conditioners and comfort fans

[7] Commission delegated regulation (EU) No 626/2011 of 4 May 2011 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to energy labelling of air conditioners

[8] Commission regulation (EU) No 813/2013 of 2 August 2013 implementing Directive 2009/125/EC of the European Parliament and of the Council with regard to ecodesign requirements for space heaters and combination heaters

[9] Commission Delegated Regulation (EU) No 811/2013 of 18 February 2013 supplementing Directive 2010/30/EU of the European Parliament and of the Council with regard to the energy labelling of space heaters, combination heaters, packages of space heater, temperature control and solar device and packages of combination heater, temperature control and solar device Text with EEA relevance

[10] http://ec.europa.eu/environment/ecolabel/products-groups-and-criteria.html

[11] Commission decision 2007/742/CE of 9 November 2007 establishing the ecological criteria for the award of the Community eco-label to electrically driven, gas driven or gas absorption heat pumps

[12] Commission Decision 2014/314/EU of 28 May 2014 establishing the criteria for the award of the EU Ecolabel for water-based heaters

Lighting

Sustainable and energy-efficient lighting systems which put human needs in the foreground: Guiding Light and iNSPiRe

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Abstract

Demographic change progresses inexorably and predicts a fast growing lifespan in the next decades [1]. To allow people a long, independent life in health and well-being, specific lighting needs have to be addressed. In particular elderly people require a multiple amount of light in contrast to younger ones [2]. Additionally holistic and efficient approaches for the refurbishment of Europe's old buildings will play a key role in future lighting solutions.

This paper gives examples of Bartenbach's efforts in order to develop new, technically innovative approaches for sustainable and energy-efficient lighting systems, **which puts the visual and biological needs of (elderly) people in the foreground**, showing the approaches of two recent research projects: Guiding Light [1]and Inspire[2].

1- Introduction to the current lighting situation of Europeans private apartments

According to countless studies focused in particular on older people, light effects (i.e. light incorporated via the eye) can be described on the following three levels [3]:

- visual light effects (allow stress-free information recording also at higher age)
- emotional lighting effects (mood by making special light environments, perch on preferred color temperature and brightness level of the elderly, considering also aesthetic lighting design and easy user interfaces [4])
- biological light effects (affect sleep, mood, physical activity, cognitive information processing and other key circadian physiological processes [5], [6]).

Some field studies in recent years were able to show that these three levels remain largely ignored within private homes (of elderly) [7], [8], [9]. Inefficient lighting in areas with increased need for visual performance shows significantly less than 500 lux horizontal illuminance. For example 500 lux are recommended at work places as minimum level. But such magnitudes are not sufficient for a stress-poor vision in old age [2]. Also the illuminance level at the eye (important for biological effects) is in general below 200 lux, especially in areas further away from the window [10], [11]. Further measurements of illumination levels executed in private houses in the course of recent Bartenbach research projects show that the typical average illuminance in the residential sector range from 50 lux to 100 lux. Indeed, in the most of the examined apartments were assessed a lack of illumination to satisfy any specific task requirements.

Summarizing, currently private homes (especially of elderly people)

- are mainly lit by daylight during the day with unevenly distributed light levels indoors (e.g. high light levels near the windows and low light levels in the back)

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[1] Guiding Light is a 3 year AAL- funded project (with national co-funding) including 6 partners in research on light assistance for spatial orientation of old people. URL: http://guiding-light.labs.fhv.at/

[2] iNSPiRe is a four-year, EC-funded project that see the collaboration of 24 partners across nine work packages from the combined fields of research and development, industry, small business and not-for-profit organizations. URL: http://www.inspirefp7.eu/

- are illuminated with artificial lighting systems in areas and rooms with a lack of daylight or for task lighting which often are not used during day- and nighttimes or provide an illumination which doesn't fulfill basic physiological lighting requirement of elderly people (e.g. glare-free higher illuminance levels).

Nevertheless, people all over Europe do not recognize their illumination at home as a significant problem. Noise from outside, pollution or high indoor temperature in summer have been named as more imported problems at home (see ***Figure 1***).

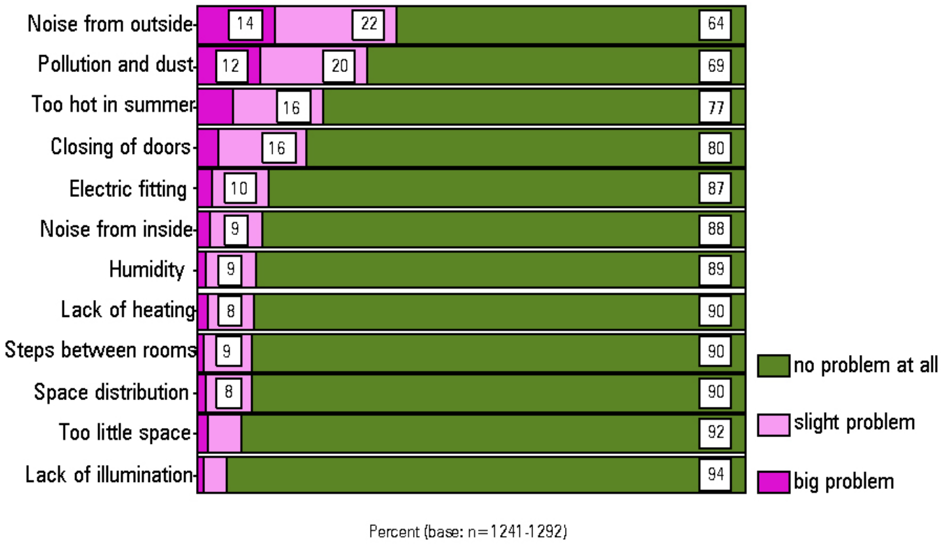

Figure 1 Subjective problems with housing [5]

With sophisticated LED based luminaires a lighting design can be applied to enhance significantly the lighting situation in private homes. Light effects of all three levels can be generated using approximately the same amount of electrical power consumption by utilizing (intelligent and LED based) dynamic lighting. Already in the last years energy saves due to the use of LED technology in residential buildings have been noticed. This was mainly driven by the ban of conventional incandescent bulbs [12]. Energy consumption can be further reduced of 40% and more by automatic lighting control (sensors) [13].

Starting from those general statements, the aim of this paper is to show a new approach in relation to psychological and physiological effects of lighting -through two current research projects- and to highlight the necessity to put human needs at the first place in the development of sustainable lighting solution.

Knowledge on human lighting needs founded on a scientific base has been the main driver to provide a significant added value to current standard approaches based on energy saving, improving the ambient quality in people everyday life.

2- New lighting for fulfilling human lighting needs in (smart) domestic appliances

With the following lighting approach we aim to establish significant improvements in domestic lighting appliances focusing on human needs, additionally to energy efficiency. In a subsequent chapter two different project implementations of this approach are shown.

Lighting design concept

The lighting concept consists of separate ambient- and task lighting (controlled separately, multitude of lighting scenarios, adapted to use cases).

Based on the daily structure (e.g. using the activities of daily life (ADL) and assigning it to the times of a usual day) of the inhabitant, a pre-adjustment of illuminance level of lighting for different day times and room zones have been set up [14]. Special attention is focused onto the increased glare sensitivity (typical of elderly). Therefore studies on brilliance have been carried out to determine the transition between perception of sparkles and negative glare. This technical feature has been considered already during the development and the implementation of the optical components into the luminaires. In order to realize a biological effect the lighting design pays attention to a well-balanced ambient brightening (realized by increased vertical illuminance levels).

2.1 Ambient room lighting

We define as ambient lighting the basic lighting of the whole room / apartment, i.e. the ambient light provides the overall minimum illumination, in order to guarantee the basic visual functions, and to move and orientate between the different spatial zones. Basically, ambient room lighting components are switched automatically in case of the presence of a person and are subject to the amount of daylight entering the room.

A control strategy is predisposed so that at the presence detection the room is illuminated very homogeneous with 300 lux and 4000 Kelvin at floor level between getting up and 2,5 hours before going (usually) to bed. Within the next half hour the colour temperature of the ambient light is reduced from 4000 Kelvin to 2200 Kelvin and the illuminance level is dimmed imperceptibly from 300 lux to 150 lux (The ultra warm-white light colour is achievable with LEDs available on the market: e.g. Cree XT-E). This is preluding the sleeping phase. Within the two hours of going to bed illuminance levels are further reduced to 50 lux (the time range of dimming is 30 min). When the bed is left during the night times rooms are illuminated with a maximum of 50 lux and a colour temperature of 2200 Kelvin. Individual adaptation to lower brightness during night times hours is possible on request of the inhabitant.

Table 1 - Overview of ambient room lighting parameters

Time	CCT [K]	(horizontal) illuminance [lux]
Day (dawn optional)	4000	300
Evening	2200	150
Night	2200	< 50

A special optional feature of the ambient lighting components in the bedroom is to simulate an artificial dawn for ease of waking up and getting up. This light alarm clock function increases exponentially the room brightness from 0 to 300 lux, starting half an hour before intended awakening and changing colour temperature from 5700 Kelvin to 4000 Kelvin.

To sum up, ambient lighting should support

- the visual needs for spatial orientation, safe navigation and strainless visual information processing and
- the non-visual needs for temporal orientation, stable sleep-/wake rhythm, vigilance and bright mood

by means of an individualized lighting control scheme.

2.2 Task lighting

As task lighting we define a zonally illumination for defined spatial zones (which are characterized with major visual needs).

Basically task lighting should always be adapted to the individual visual needs of the inhabitant with illuminance levels up to 2000 lux. This task light control strategy is based on an exclusive manual operation. For a comfortable and frequent use of the task lights, the corresponding light switches are mounted within reach of the tasks. From getting out of bed to 2,5 hours before going to bed again task lighting is switched on manually and a predefined optimal brightness level with 4000 Kelvin illuminate the task areas. Over a time span of 30 min task lighting is changed indiscernibly in colour temperature from 4000 Kelvin to 2200 Kelvin and the optimal daytime brightness is dimmed to a third. This setting of the zonally lighting remains during the evening and night. Again brightness levels of the task lighting components can be further reduced at the request of the inhabitant during night times.

Table 2 - Overview of task lighting parameters

Time	CCT [K]	(horizontal) illuminance [lux]
Day	4000	1000 (up to 2000)
Evening	2200	300 (up to 1000)
Night	2200	< 300

3- Implementation of energy-efficient lighting focusing on human needs: results from research projects

3.1 Guiding Light

Guiding Light focuses on the development of an intelligent light assistance system for domestic use, especially for elderly people. Light is used to meet visual needs (e.g. decrease risks of falling), is applied for temporal orientation (e.g. stabilizing circadian rhythm) and for spatial navigation (e.g. illumination of defined areas). Light, therefore has great potential for attenuation of age-related mobility impairments caused by reduced spatial-temporal orientation.

The lighting design approach, comprising indirect and direct lighting and including a dynamic control scheme (time-controlled change of brightness and light colour) was implemented into 11 test apartments in Austria, Germany, Switzerland and Italy. A comparison group of 8 households was evaluated. This means in total 19 test apartments were evaluated by a field study. The basic houses were spread over four different countries and this generated experience with different languages (German and Italian) as well as experiences with different legal and cultural initial situation in order to be prepared for a scale-up.

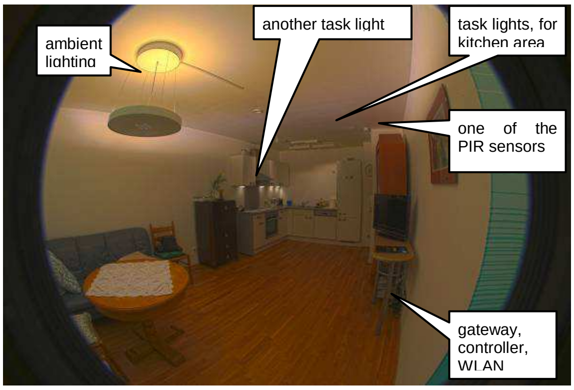

Figure 2 View into a field test apartment before and after the installation of "Guiding Light"

These two pictures of Figure 2 shows the comparison of one apartment before and after the installation of a whole Guiding Light system. A whole Guiding Light system consists out of the following components: lighting design, luminaires of five different types, radio switches, wireless sensors (motion including illuminance and door contact), gateway and Internet connection, control algorithm configured onto a cloud computing system.

The automated ambient light switching is implemented with passive infra-red (PIR) sensors, which are detecting changes in motion of objects radiating heat. Consequently, a special algorithm determines the probability of room occupancy on the basis of recently transmitted PIR sensor data, i.e. presence detection isn't only depending on motion detected by PIR sensors. "Static" situations (e.g. the inhabitant is reading and doing only very small hand or arm movements) can be treated by the system with occupancy algorithms. In order to improve comfort and well-being (of elderly people) a special strategy for bedroom ambient and task lighting has been defined. The approach is based on investigation results carried out at Bartenbach. A light switch close to the bed basically allows the manual switching of the bedroom lighting during the night hours. As a consequence, the ambient lighting component in the bedroom should be turned off manually by the older person. Information on the typical times in bed over the last four weeks are used to establish an individual lighting control algorithm for the ambient lighting components which both varies the light intensity and colour temperature of the lighting depending on individual sleep-/wake rhythm. The task lighting components in defined spatial zones with major visual needs must be switched manually.

Mobility parameters of the inhabitants were monitored and the results of analyzing these data was be used in two different approaches: a) to change the programming of light variations, b) to verify the hypotheses of the described human light impact. The system impact on the inhabitants was evaluated by a field study which run over a period of more than 12 months (study end date: April 2015).

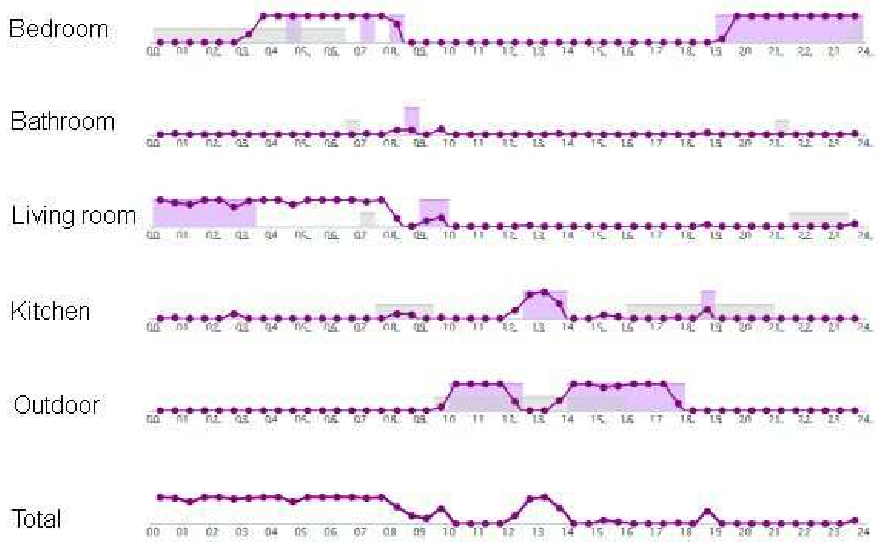

Figure 3 Screenshot of web based monitoring tool in expert view (i.e. not shown to the inhabitants), it shows the amount of motion detections and real room occupancy (violet marks) and foreseen daily structure (grey marks)

An online visualisation was developed (see Figure 3). It shows the amount of motion which was detected for different room zones. Out of this a set of parameters (room zone stay, outdoor stays, amount of mobility, sleep time, etc.) is calculated and shown in the "expert view". This gives at any time insight to these kind of "health information" and can be shared with persons of trust (e.g. relatives, doctor, etc.). It is not shown directly to the inhabitants, therefore a simplified view was used.

This means the "degree of mobility" is an indicator of health [16], [17].

3.2 iNSPiRe

As depicted in the introduction, residential inhabitants live in poorly illuminated environments. The project iNSPiRe defines a new approach showing that in domestic lighting appliances at least, zoning (i.e. increasing illuminances according to specific tasks) is absolutely necessary for an improved (visual) comfort, while not contradicting the idea of reducing energy. Additionally, the term of 'brillance' and its effects on objects perception have been investigated to enhance the impact of the developed technologies.

Illuminance levels have been related to the standard room dimensions of private apartments with the aim to fulfil the described lighting design. According to those main requirements, the development of new lighting solutions have been carried out evaluating sparkle effects and the possibility of glare due to brilliance. For this reason, the parameters of brilliant appearance relative to residential lighting have been defined as listed in table 3, where have been identified values of luminance alteration ΔL, visual angle $\Delta\Omega$ and luminance gradients $\vec{\nabla} L$ influencing sparkle phenomena. Those parameters, together with geometrical and ambient factors have been design drivers in the development of new sophisticated lighting technologies.

Table 3 Main variables influencing overall appearance and phenomena of sparkle.

Parameter	Values
$\vec{\nabla} L$	for sharp luminance profile; $\|\vec{\nabla} L\|$~10^{10}cd/(m² rad)
$\Delta\Omega$	for small "glossy points" ; <1'
ΔL	for large luminance alteration, > 10^{7}cd/m² (except very small glossy points)

The combined requirements mentioned above result in the development of customized luminaires ready to be integrated into multifunctional prefabricated ceiling panels. In addition a multi-criteria analysis has been defined in order to set up an overall refurbishment strategy.

The research process results in the development of two main luminaires:

- a suspended luminaire with advanced optic components for living/dining rooms
- a LED spotlight solution called “recessed luminaire”

In order to improve comfort as well as to optimize the light impact, the luminaires allows to vary intensity, correlated colour temperature (Melatonin-adapted in night times), and the light intensity distribution (varying direct-indirect component, being adaptable to the subjective users demand).

Pendant (suspended luminaire)

Lighting a whole room out of one single point located on the ceiling is not possible without the insurgence of glare problems. Starting from the objective to illuminate living rooms out of one single position ensuring comfort, a pendant luminaire based on an advanced lens system has been developed within iNSPiRe. The research design process has been carried out with the ambition to provide specific task-zone lighting combined with a well balanced indirect illumination and to avoid disability glare as well as sparkle discomfort effects. Thanks to a hybrid optics light engine combined with a complex surface lens system, the resulting luminaire produces a structured luminance distribution at the ceiling (atmosphere lighting) as well as a perfect non-glaring zoning on the specific task area. Almost 25% of the light which hits the plate (~ max. 1150lm) can be controlled by the spherical reflective surfaces, creating a well-balanced luminance between the indirect light homogeneously distributed by the plate and the lighting patterns.

No disturbing sparkle effects are perceived by the observer in every point of the selected room area. Furthermore, multi-shadow effects are reduced and the optical design results in comfortable and controlled LIDs (luminous intensity distribution).

Figure 4 Rendered visualization of the pendant luminaire with wo possible patterns investigated.)

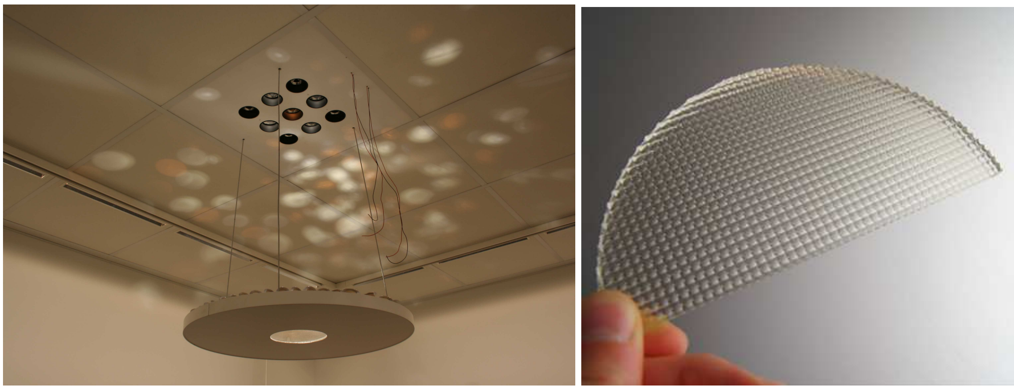

Figure 5 Mock-up of the pendant luminaire (indirect and direct lighting distribution); 3D printed lens (indirect light distribution)

Recessed luminaires

Spheres luminaires are conceived to be installed as general lighting as well as to be applied in specific spatial zones (corridors, shelves, etc.). According with the general Bartenbach approach described in chapter 2, main peculiarity of the optical development has been to ensure highly glare-free properties. A facetted reflector technology has been optimized by the use of advanced complex surface design. Thermal tests show that due to lower temperatures because of the integration into the active panel, the efficacy and lifetime of those LED spots increase by approximately 3%.

The recessed luminaire can be smoothly integrated into every kind of ceiling panel and 3D rotated of 25 degrees to allow the user the full flexibility in positioning the light source according to his/her needs without varying the anti-glare properties. Correlated color temperature can vary from 2200 to 5000K and allows to set different dynamic lighting scenaria.

Figure 6 Photo of a sample of the recessed luminaire: sphere of aluminium holding the reflector

The recessed luminaires are particularly suitable to retrofit intervention and can be installed from the bottom side of a suspended ceiling panel. Having a diameter of max. 50 mm and a maximum height of 30 mm, spheres can be integrated in standard active ceiling available on the market.

Summary

Within the segment of private apartments the application of LED lamps is strongly increasing, i.e. this is reducing in general the energy consumption. But simple retrofitting is not enough to generate any added values. Numerous studies are showing the poor illumination situation in private homes and the missing awareness of this situation for the majority of those affected.

With the presented research projects we demonstrate the implementation of new lighting which improves significantly the comfort and wellbeing of the inhabitants without increasing the energy consumption.

In particular in Guiding Light it turns out that for conversion from conventional house lighting to LED based lighting by considering constant energy consumption more than six times as much "light flux" can be implemented (LED and luminaire efficiency of 2014), i.e. the threshold for "partial biologically active illumination" is achieved, at constant energy costs. Furthermore within Guiding Light a dynamic lighting system for residential use was successfully implemented in private homes.

Within the project iNSPiRE the aim is to reduce the lighting energy consumption by at least 50% and the primary energy consumption in a building to 50kWh/m²/year although the human lighting needs are put in the foreground. In iNSPiRE this goal is achieved by considering zonal lighting design and by the development of sophisticated luminaires (pendant and recessed luminaire integrated into ceiling panels dedicated to refurbishment). Inspire shows that industrialization and development of standard components can be well combined with the production of high quality luminaires, able to ensure high comfort levels and high energy performances at a market price.

Through intelligent control algorithms and daylight sensors further potential energy savings can still be lifted. However, this is associated with too much increased investment costs, and from today's perspective for private homes not yet ready for the market.

Acknowledgment

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Luminaire efficiency: what mandatory and voluntary labels achieve, and what they should achieve in the future

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Abstract

The European Union (EU) energy label for household luminaires is relatively young; 2014/2015 is the second retail season during which it is available for consumers. This label differs from all other mandatory EU energy labels in that it does not refer to the product's annual energy consumption or energy efficiency. Instead it indicates only the energy efficiency class of light sources (lamps) included in the luminaire and available alternatives. Existing ecodesign regulations require only information about the LED module alone to be provided with luminaires. This is misleading because light is lost in diffusors and shades, and components for power conversion and lighting control use extra energy.

This paper discusses measurement results for about 200 luminaires evaluated by the voluntary Topten label during the last two years. Since 2009 the energy efficiency project „Topten" has collaborated with Switzerland's two largest retailers, Coop and Migros, as well as other suppliers and manufacturers in labelling the best household luminaires in shops and catalogues. Light output, power and colour spectrum are measured for the label.

The measurement results show that there are large saving potentials in household luminaires which are currently not communicated to consumers. Luminaire efficiency ranges from 10 - 100 lumens per watt; and standby energy consumption is common and sometimes unnecessarily high. Measured colour rendering values of LED luminaires were generally good though could improve.

The paper conludes with recommendations for retailers and policy makers on how to provide better consumer information on household luminaires. Specific improvement options for the EU energy label and ecodesign requirements for luminaires are identified.

Introduction

The EU energy label provides key information about energy consumption and efficiency performance of many energy using products. Despite a new label, the luminaires we buy for our homes use more energy than stated on the packaging. Seldom there is information on standby power. 0.5 watt in off-mode (standby-mode) annually consumes 4 kWh; for a 10 watts LED luminaire, this adds 40% to energy costs[1]. Another cause of misleading information is that power is declared for the LED module alone; power of components for power conversion and lighting control (e.g. drivers, touch-sensors, etc.) are usually omitted. These typically add another 1-2 watts to the luminaire's total power. Even more misleading are declared lumens (luminous flux). They too are given for the LED module alone. Typically 5-70% of the light is lost inside the luminaires' shades and diffusors. A luminaire that is declared at 550 lumens (approx. equivalent to a 45 watt incandescent bulb) might really only deliver 300 lumens (see examples in Table 1). Consumers might chose an unsatisfying luminaire when LED lamps are built-in and cannot be replaced.

This paper will briefly outline the EU energy label and the voluntary Topten label for luminaires; it will discuss measurement results for about 200 tested luminaires; and then make recommendations for better consumer information on household luminaires (both for EU policy and retailers).

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[1] 1 year = 8760 hours. 10 watts during 1000 hours/year + 0.5 watt during 7760 hours/year = 10 kWh (use-mode) + 4 kWh (standby-mode) annually.

On packaging: 3 x 2.5 W 550 lumens	Measured: 8.5 W (+13%) 299 lumens (-46%)	On packaging: 31.2 W ca. 3700 lumens	Measured: 31.0 W (-1%) 2463 lumens (-33%)

Table 1: Typical examples of luminaire packaging and differences to actual watts and lumens

EU energy label

The EU energy label for household luminaires, EU regulation No 874/2012 [1], is relatively young. It has been in use during two retail seasons (winter 2013/2014 and winter 2014/2015). This label differs from all other mandatory EU energy labels since it does not refer to the product's energy consumption, light output or energy efficiency. Instead it indicates only the energy efficiency class of light sources (lamps) included in the luminaire and available alternatives. There are numerous designs for the label reflecting the variety of light sources. Figure 1 shows a selection of them.

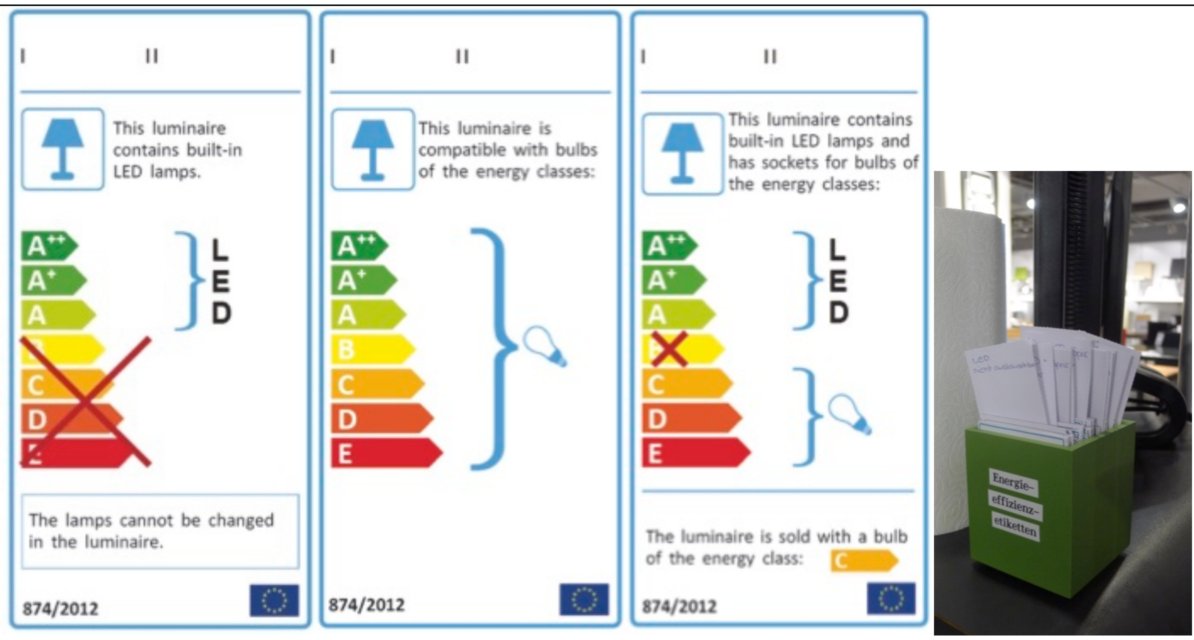


Figure 1: EU energy label for household luminaires according to EU regulation No 874/2012 [1] (selection of possible designs). On the right: box with labels in a luminaire shop.

You will see later in this paper that we propose to apply the EU energy label for lamps also to luminaires with built-in LEDs. Unlike the luminaire label, the label for lamps comprises an actual rating of the product's energy efficiency. The calculation of the energy efficiency index is shown in Figure 2. Several choices for power correction and useful luminous flux make the calculation rather complicated.

For the calculation of the energy efficiency index (EEI) of a model, its power corrected for any control gear losses is compared with its reference power. The reference power is obtained from the useful luminous flux, which is the total flux for non-directional lamps, and the flux in a 90° or 120° cone for directional lamps.

The EEI is calculated as follows and rounded to two decimal places:

$EEI = P_{cor}/P_{ref}$

where:

P_{cor} is the rated power (P_{rated}) for models without external control gear and the rated power (P_{rated}) corrected in accordance with Table 2 for models with external control gear. The rated power of the lamps is measured at their nominal input voltage.

Table 2

Power correction if the model requires external control gear

Scope of the correction	Power corrected for control gear losses (P_{cor})
Lamps operating on external halogen lamp control gear	$P_{rated} \times 1{,}06$
Lamps operating on external LED lamp control gear	$P_{rated} \times 1{,}10$
Fluorescent lamps of 16 mm diameter (T5 lamps) and 4-pin single capped fluorescent lamps operating on external fluorescent lamp control gear	$P_{rated} \times 1{,}10$
Other lamps operating on external fluorescent lamp control gear	$P_{rated} \times \frac{0{,}24\sqrt{\Phi_{use}} + 0{,}0103\Phi_{use}}{0{,}15\sqrt{\Phi_{use}} + 0{,}0097\Phi_{use}}$
Lamps operating on external high-intensity discharge lamp control gear	$P_{rated} \times 1{,}10$
Lamps operating on external low pressure sodium lamp control gear	$P_{rated} \times 1{,}15$

P_{ref} is the reference power obtained from the useful luminous flux of the model (Φ_{use}) by the following formulae:

For models with $\Phi_{use} < 1\,300$ lumen: $P_{ref} = 0{,}88\sqrt{\Phi_{use}} + 0{,}049\Phi_{use}$

For models with $\Phi_{use} \geq 1\,300$ lumen: $P_{ref} = 0{,}07341\Phi_{use}$

The useful luminous flux (Φ_{use}) is defined in accordance with Table 3.

Table 3

Definition of the useful luminous flux

Model	Useful luminous flux (Φ_{use})
Non-directional lamps	Total rated luminous flux (Φ)
Directional lamps with a beam angle ≥ 90° other than filament lamps and carrying a textual or graphical warning on their packaging that they are not suitable for accent lighting	Rated luminous flux in a 120° cone ($\Phi_{120°}$)
Other directional lamps	Rated luminous flux in a 90° cone ($\Phi_{90°}$)

Figure 2: Calculation of the energy efficiency index for lamps according to EU regulation No 874/2012, Annex VII [1]

Topten label

Since 2009 suppliers and manufacturers have collaborated with the energy efficiency project „Topten“ to label the best household luminaires (Figure 3). Among them are Switzerland’s two largest retailers, Coop and Migros. The luminaires are tested for energy efficiency, standby power, light colour (also called colour temperature) and colour rendering. Only products that meet Topten’s ambitious criteria (Table 2) are then labeled as energy-saving, eco-friendly articles in the shop. They are also published on the Topten website (Figure 4).

Figure 3: The Topten logo showcases the most energy efficient household luminaires in shops

Luminaire efficiency factor	>= 50 lumens per watt except when >90% indirect lighting >= 55 lumens per watt
Standby power	<= 0.5 W except when luminaires have an in-built dimmer <= 1.0 W
Colour rendering index (CRI)	>= 80 (only for luminaires using LED)
Colour temperature	<= 6500 kelvins (only for luminaires using LED)

Table 2: Criteria for energy efficient household luminaires defined by Topten [4]

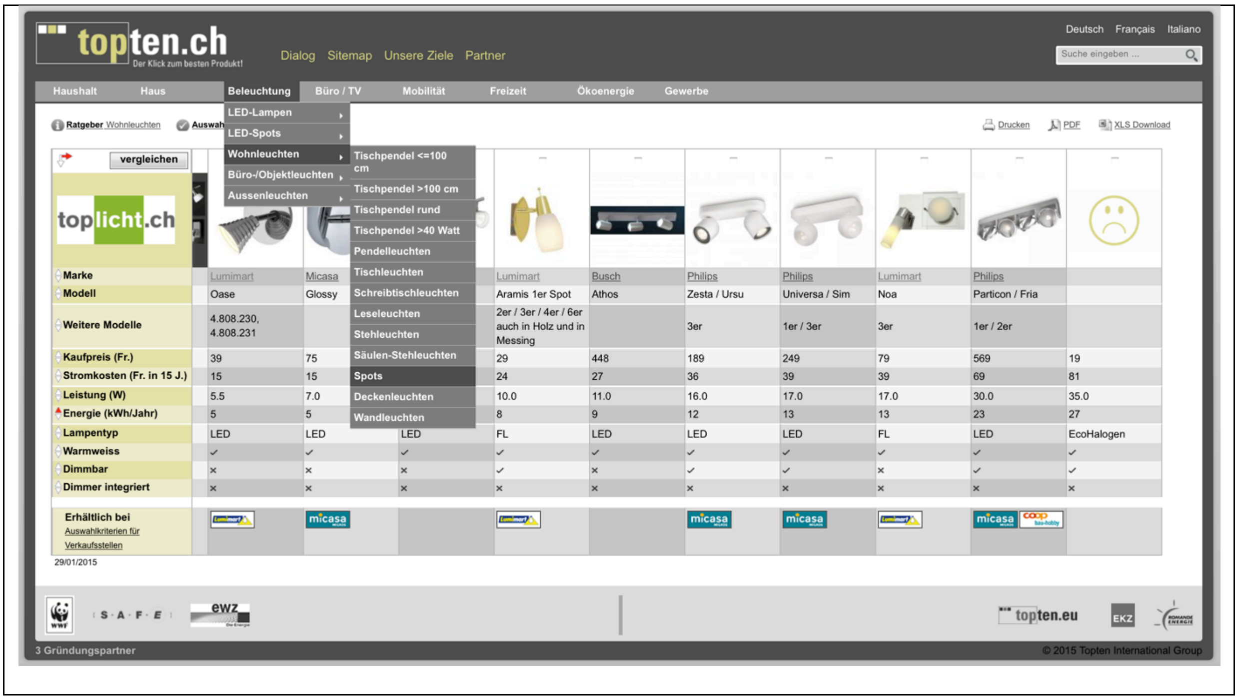


Figure 4: The Topten website publishes the lists of the most energy efficient household luminaires

Measurement results for 193 household luminaires

This chapter presents and discusses measurement results from the last two years, submitted for the voluntary Topten label for household luminaires. Testing was done at the Swiss Alpine Laboratories for Testing of Energy Efficiency (S.A.L.T.) in Chur, Switzerland [5]. Retailers and manufacturers chose for testing a total of 193 luminaires expected to be highly energy efficient (since they should meet the Topten criteria and be accordingly labelled in the shops). Therefore the dataset consists of mostly LEDs (158 built-in, 6 retrofit GU10) and some luminaires with compact or linear fluorescent lamps (29). Luminaires with incandescent or halogen lamps were not evaluated because they cannot meet the Topten energy efficiency criteria. The majority of luminaires are "directional" (here we call them "directional" when >90% of the light output is within a cone with angle of 180° [2]). However "directional" does not mean that they are all meant for accent lighting. In fact, most of them are designed for general lighting. It is typical that light output of LED luminaires is distributed in a semi-sphere instead of a whole sphere like we are used to from incandescent, halogen or fluorescent lighting. See light distribution categories used by Topten in Table 3 and luminaire types in the data set shown in Figure 5.

[2] This includes slightly more luminaires than the definition of directional lamps in EU regulation No 874/2012 (energy labelling of lamps) which states: 'Directional lamp' means a lamp having at least 80% light output within a solid angle of π sr (corresponding to a cone with angle of 120°).

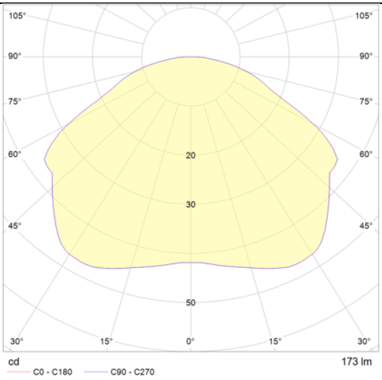
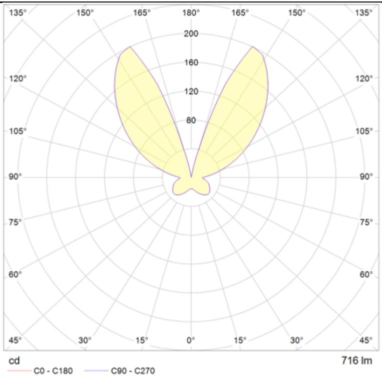
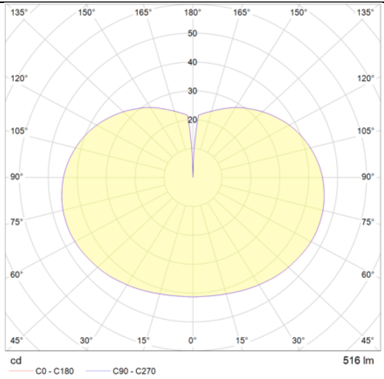
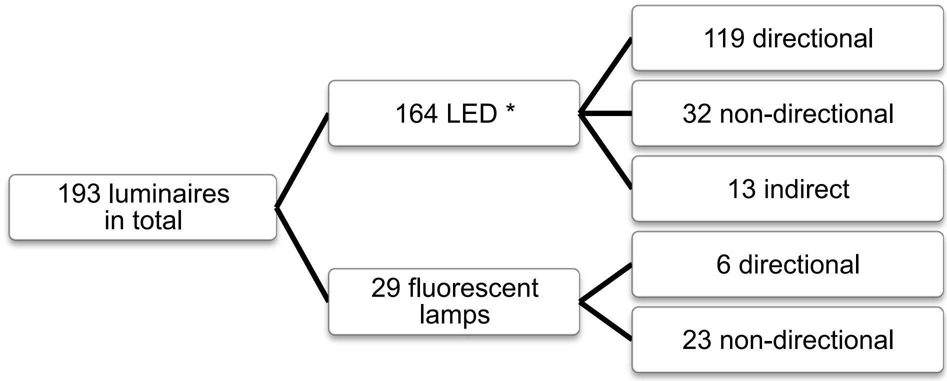
		
directional = 90 % of the light output is within a downward cone with angle of 180°	indirect = 90 % of the light output is within a upward cone with angle of 180°	non-directional = everything else

Table 3: Light distribution categories used by Topten



* 158 built-in and 6 retrofit GU10

Figure 5: Overview of luminaire types in the data set

Test methodology and results

The luminaires were tested in a climatised room with stabilised electrical power supply. Equipment and tested parameters:

- Power meter (Voltech Poweranalyzer PM1200): power in use-mode (watts), power in standby-mode (watts), power factor (-)
- Spectroradiometer (Specbos 1201): colour temperature (kelvins), colour rendering (-), colour spectrum (image file)
- Photogoniometer (engineered by HTW Chur, lux meter Minolta T10): total luminous flux (lumens), light distribution curve (image file and .ldt file)

Power and luminous flux, colour temperature

The 193 household luminaires are characterised by power generally no higher than 40 watts and lumens no higher than 2600 lumens (see Figure 6). As expected most LED luminaires are warm white while only 12 are neutral white (popular for bathrooms for example) and (again) 12 are daylight white (popular for desk lighting for example):

- warm white = colour temperature <3500 kelvins
- neutral white = colour temperature 3500-5000 kelvins
- daylight white = colour temperature >5000 kelvins

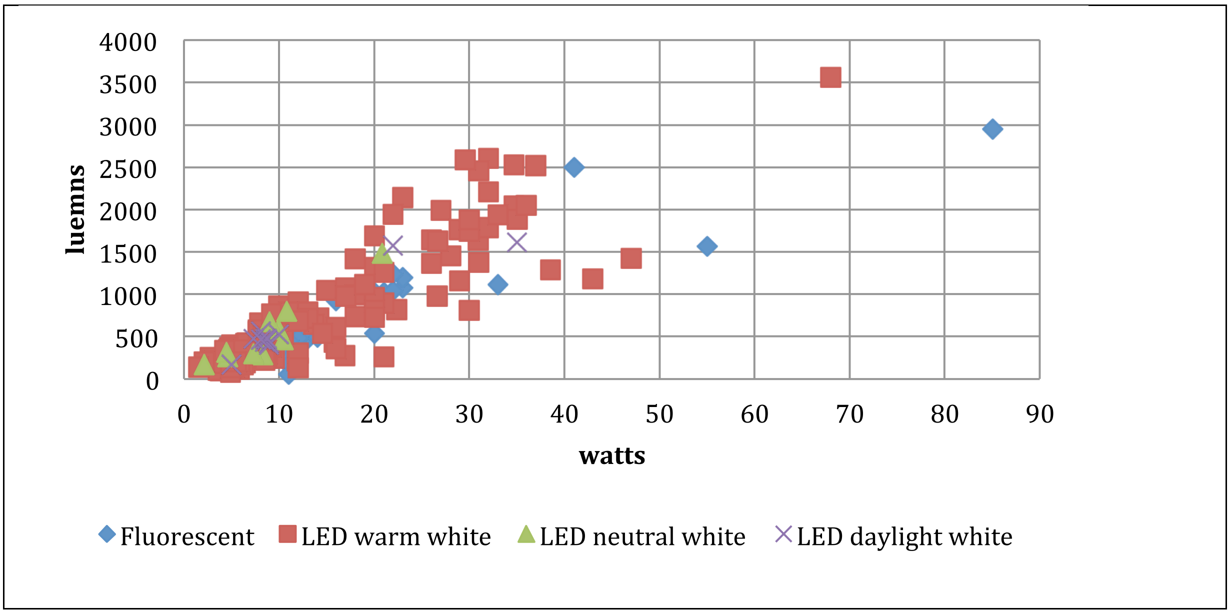


Figure 6: Measured watts and lumens for the 193 tested luminaires

Declared lumens on packaging compared to measured lumens

For the 131 LED luminaires for which there was a lumens value declared on the packaging, the declared and measured values were compared. Figure 7 shows that declared lumens are in many cases substantially higher than measured lumens.

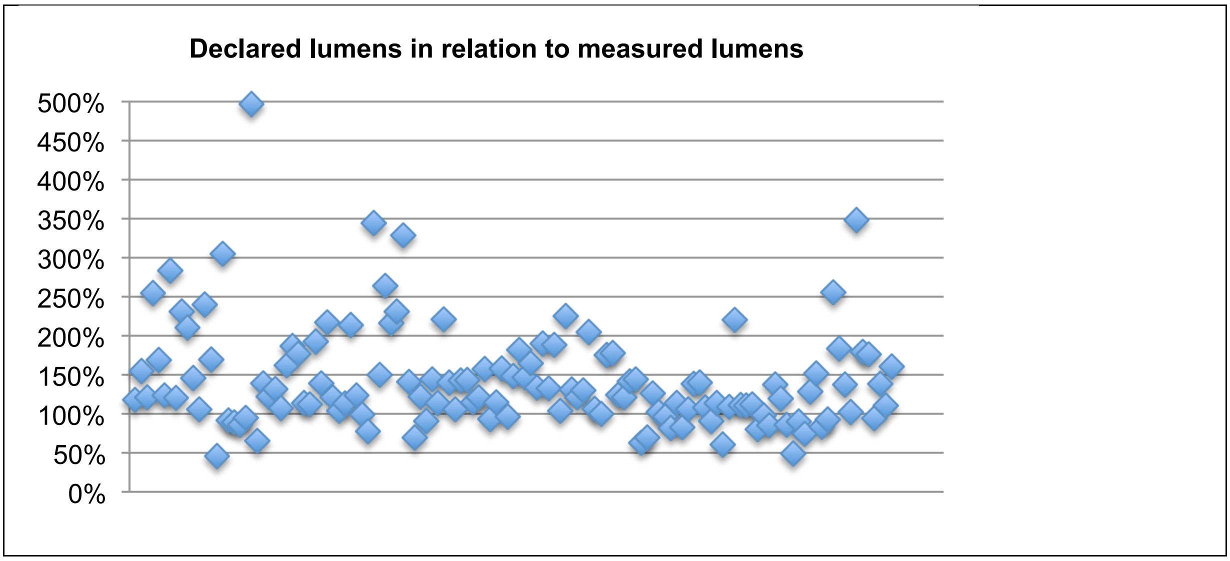


Figure 7: Lumens declared on packaging compared to measured lumens (100% = measured) for 131 LED luminaires (no declaration available for rest)

Luminaire efficiency factor (lumens per watt)

Luminaire efficiency is expressed by the ratio of total luminous flux in lumens and total power in watts. This ratio is also called luminaire efficiency factor (LEF). Measured efficiency ranges from 10 – 100 lumens per watt. The best result for luminaires using LED is 96 lm/W, and for luminaires with fluorescent lamps it is 61 lm/W (Figure 8).

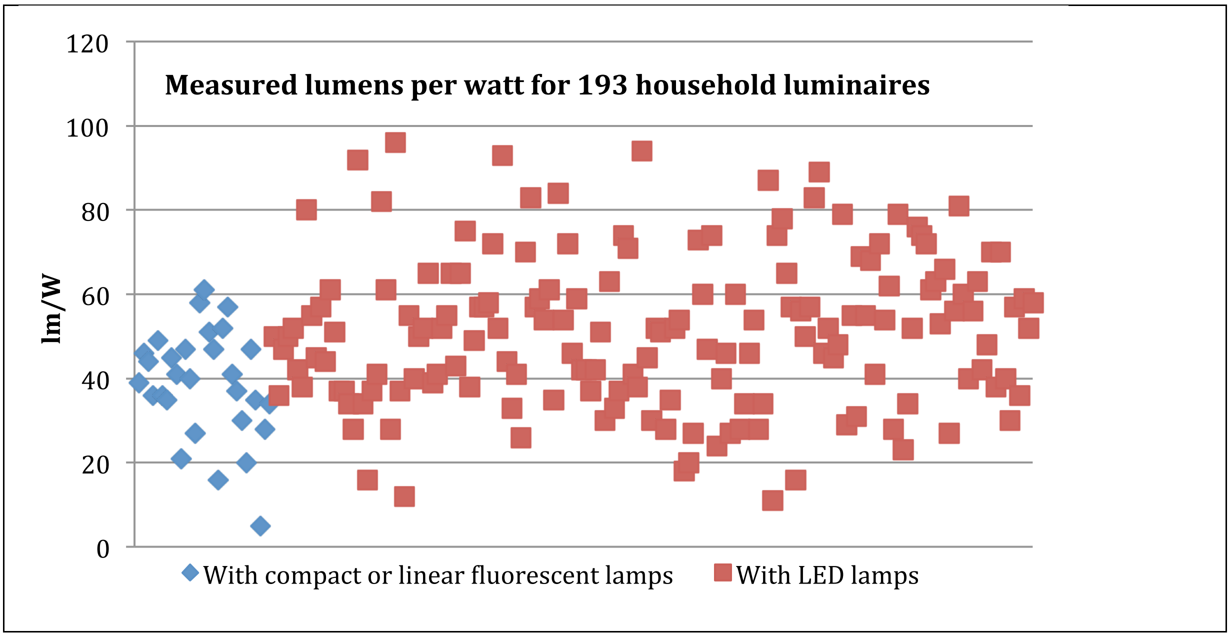


Figure 8: Measured lumens per watt for 193 household luminaires

Applying energy efficiency classes to LED luminaires

For the 158 luminaires with built-in LEDs, the energy efficiency class was calculated as if they were lamps (Annex VI and Annex VII in EU regulation No 874/2012 [1], see also Figure 2). This revealed that 21 luminaires would be in class B and 2 in class C (Figure 9). The EU energy label fails to show this; instead it presents the notion that all luminaires with built-in LEDs are in classes A, A+ or A++ (Figure 1). The savings are large and consumers would certainly benefit from being aware of these. A luminaire in class A++ saves:

- over 80% compared to class B or C
- over 50% compared to class A
- over 25% compared to class A+

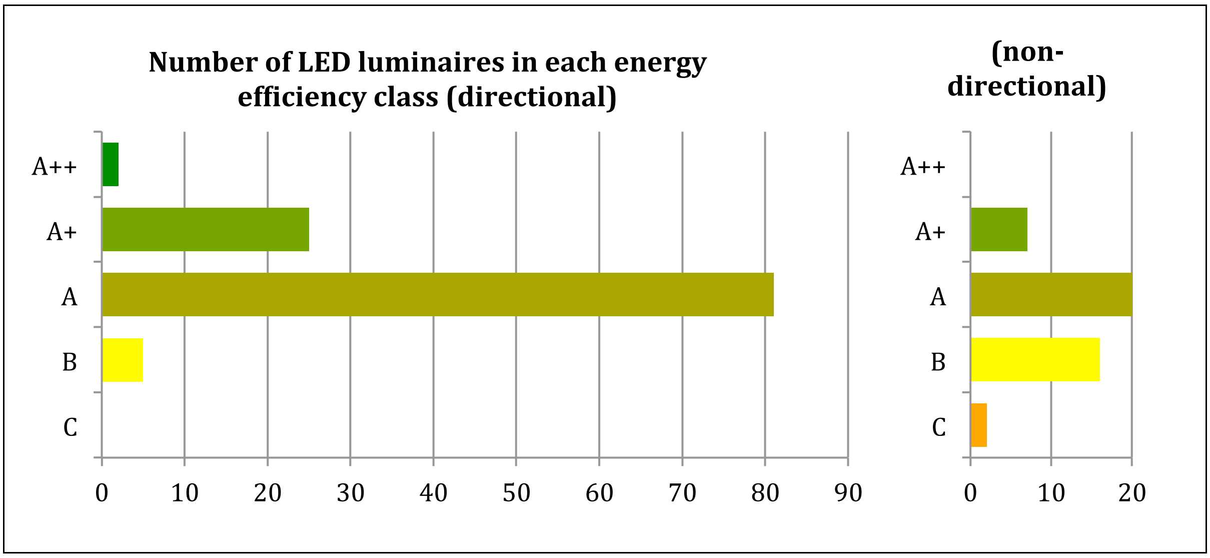


Figure 9: Number of LED luminaires in each energy efficiency class

Standby

Every third tested luminaire consumes energy in off mode. Measured standby power tends to be around 0.5 watts (Figure 10). A few tested products consume more than 1 watt in off mode, and maximum standby power was measured at 3.6 watts. Standby energy use is very common among floor-standing, table and desk luminaires (57 of 77 tested products). Wall or ceiling mounted luminaires seldomly consume standby energy (6 of 116 tested products); when they do, it is typically because additional light switches, dimmers etc. are built into the luminaire.

In the EU, standby consumption is partially limited through requirements for control gear and ballasts in regulations No 1194/2012 [2] and No 245/2009 [3]. The limits are 0.5 watts for fluorescent lamps' ballasts (without integrated ballast) and 1.0 watt for other power converters like halogen convertors and transformers and LED drivers (0.5 watt as from 1 September 2016). A summary of the respective requirements is given in Table 4: Energy efficiency requirements for lamp control gear and ballasts.

Other luminaire components can add to standby energy consumption. Typically they are components for lighting control like timer switches, occupancy sensors, light sensors and daylight regulation devices or illuminated switches. All these are not covered by EU requirements. In addition, phase cut dimmers are also exempt from the requirements; this means that practically all dimmers are exempt. Leading edge phase cut dimmers are commonly used with conventional power converters for halogen and incandescent lamps; trailing edge phase cut dimmers are used with electronic power converters for fluorescent or LED lighting.

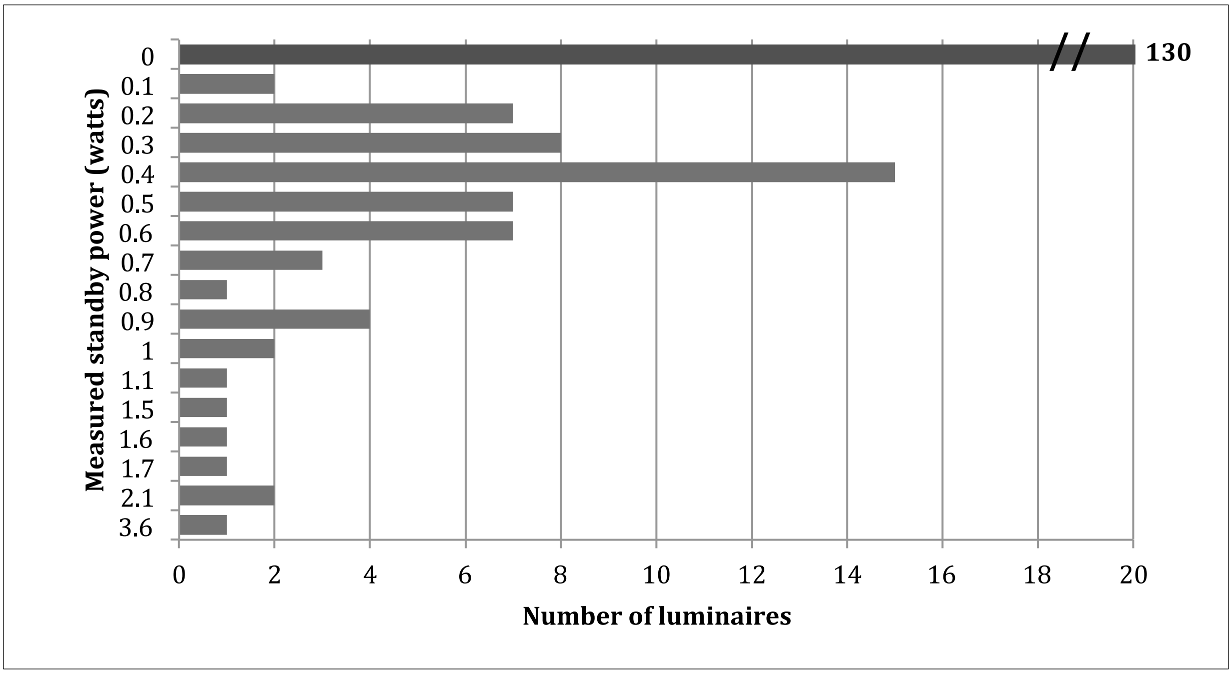


Figure 10: Measured standby power in watts

Colour rendering

The colour rendering index (CRI) is a measure of how colours appear in artificial light compared to daylight. The best value is 100[3] and typically reached by halogen lamps. Values between 77 and 86 are accepted as good and typically reached by fluorescent and LED lamps. To enter the EU market LED lamps must have a CRI value of at least 80 (EU regulation No 1194/2012 [2]). LED lamps can reach excellent CRI values of nearly 100, however there is a trade-off with luminous efficiency. With the astonishing technological development of luminous efficiency in the last years (LED lamps reaching over 100 lumens per watt), demand for LED lamps with excellent CRI could increase in the coming years.

Most of the 164 measured LED luminaires showed a good CRI of 80 or higher (Figure 11). Still 1 in 5 had a lower CRI (32 products). In many cases this is likely due to lamp shades and diffusors that can reduce colour rendering quality; however in some cases where the LEDs are barely covered we suspect that there are also bad LEDs with lower CRI than allowed.

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[3] Note that CRI is not a value in percent. There can be negativ values as well.

The CRI value is an average calculated for 8 pastel colours. To only consider pastel colours is arguably not the best evaluation of colour rendering. There are 7 additional sample colours that would ideally be considered as well. They are saturated colours, leaf green and two skin colours. The saturated red, and to a lesser degree the saturated blue, rarely appear natural in fluorescent or LED light. See Figure 12 with all 15 sample colours and examples of typical CRI values for fluorescent and LED lamps.

The 164 measured LED luminaires were screened for exceptionally good colour rendering. Excellence in colour rendering was defined as:

- Ra (average of 8 pastel colours) must be >=87 and
- each of the 7 additional colours muste be >=50.

Based on these criteria, 12 of 164 products (less than 10%) could be identified to have excellent colour rendering. Figure 12 shows examples of the detailed CRI values for different luminaire types.

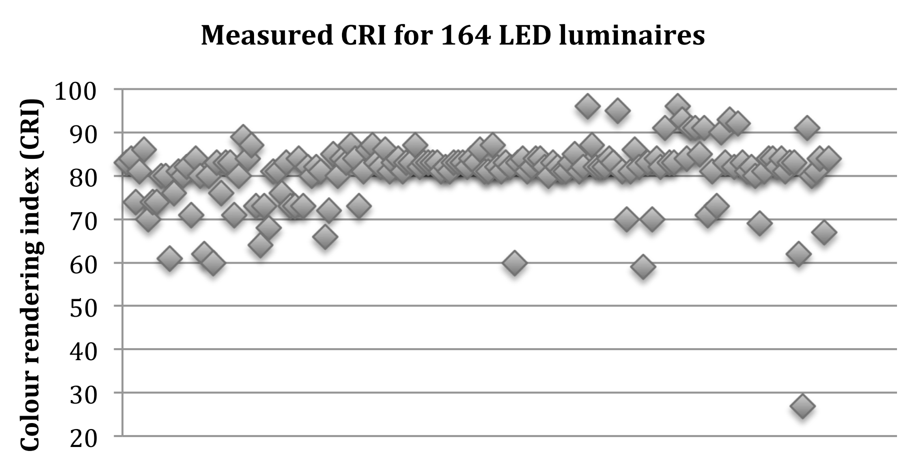
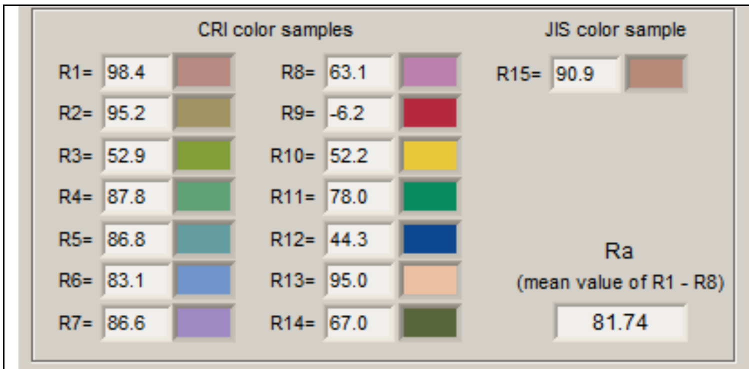
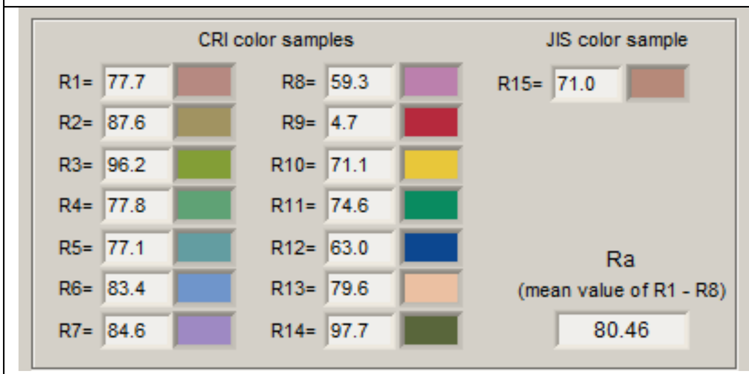


Figure 11: Measured colour rendering index (CRI) for 164 LED luminaires



Typical luminaire with fluorescent lamp



Typical LED luminaire

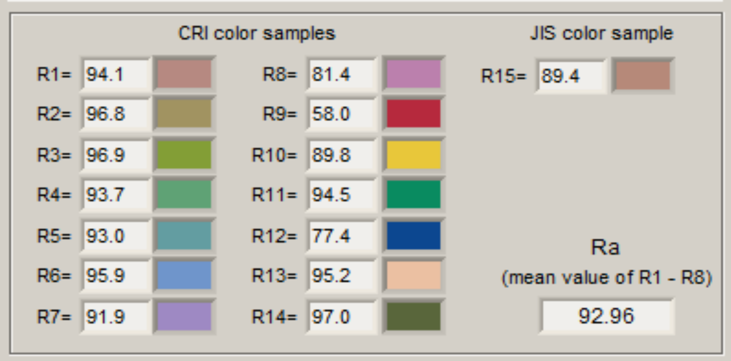
	LED luminaire with excellent colour rendering

Figure 12: Colour rendering index (CRI) values for typical examples of different luminaires

Regulation (EC) No 245/2009 [3]

Since 2012: The power consumption of **ballasts** used with fluorescent lamps without integrated ballast shall not exceed 0,5 W when operated lamps do not emit any light in normal operating conditions. This requirement shall apply to ballasts when other possible connected components (network connections, sensors etc.) are disconnected.

Regulation (EU) No 1194/2012 [2]

As from stage 2 (1 September 2014), the no-load power of a **lamp control gear** intended for use between the mains and the switch for turning the lamp load on/off shall not exceed 1,0 W. As from stage 3, the limit shall be 0,50 W. For lamp control gear with output power (P) over 250 W, the no-load power limits shall be multiplied by P/250 W.

As from stage 3 (1 September 2016), the standby power of a **lamp control gear** shall not exceed 0,50 W.

'lamp control gear' means a device located between the electrical supply and one or more lamps, which provides a functionality related to the operation of the lamp(s), such as transforming the supply voltage, limiting the current of the lamp(s) to the required value, providing starting voltage and preheating current, preventing cold starting, correcting the power factor or reducing radio interference.

(Ballasts, halogen convertors and transformers and Light Emitting Diode (LED) drivers are examples of light source control gears.)

Exempt are 'control devices':

'control device' means an electronic or mechanical device controlling or monitoring the luminous flux of the lamp by other means than power conversion, such as timer switches, occupancy sensors, light sensors and daylight regulation devices. In addition, phase cut dimmers shall also be considered as control devices;

Table 4: Energy efficiency requirements for lamp control gear and ballasts

Conclusions and recommendations for provision of better information to consumers

For EU policy

The luminaire tests discussed in this paper show that there are large saving potentials in household luminaires, but they are currently not communicated to consumers. Even within LED luminaires, which might be assumed to be energy efficient generally, the luminaire efficiency factor ranges from 10 - 100 lumens per watt; thus LED does not automatically mean "energy efficient". The EU energy label should make these saving potentials visible.

In the mid-term, we therefore recommend to update the existing EU energy label for household luminaires with a real rating of luminaire efficiency (based on measured luminaire data and the calculation of an energy efficiency index). Currently it is the only existing label that does not give any information on energy consumption or energy efficiency of the product it concerns.

In the short-term, we propose the inclusion of luminaires with built-in LEDs into the scope of EU regulations No 1194/2012 (ecodesign of directional lamps and LED lamps) and No 874/2012 (labelling of lamps and luminaires) at the next possible opportunity (e.g. the ongoing review of these regulations in 2015), so they will be treated in the same way as LED lamps. Information as well as minimum requirements for luminaire standby power should be added for all luminaires (maximum 0.5 watts for luminaires in total, including integrated dimmers, touch-switches, sensors etc.).

The market share of luminaires with built-in LED lamps is growing. Since these lamps cannot be changed it is important that consumers have the best possible product information. Actual luminous flux, total power, annual energy consumption (including standby-mode) and colour rendering are key pieces of information that are currently not available to consumers. In addition, life time and number of switching cycles until early failure are crucial information to chose durable products that can satisfy over many years. All these pieces of information would be provided to consumers with the above described amendments of EU regulations No 1194/2012 and No 874/2012. Additional benefit for consumers could be generated if annual energy consumption was declared for all luminaires (for example based on 1000 hours in use-mode and 7760 hours in standby-mode).

Standby energy consumption is common in household luminaires. The test results show that 1 in 3 luminaires consumes energy in standby-mode. We also noted that standby energy consumption is not part of mandatory product information and is not communicated to consumers, even though it substantially increases annual energy consumption of the product. Minimum requirements only partially cover standby energy consumption via the requirements for control gear and ballasts, but not standby energy consumption of dimmers, illuminated switches etc. This is insufficient since there are currently luminaires with up to 3.6 watts standby power, which is unnecessarily high.

For retailers

The test results show that colour rendering of LED luminaires is generally good and in some cases excellent. However, retailers are advised to double-check the colour rendering index (CRI) of all LED luminaires in their assortment (good portable radiospectrometers are available starting at 2000 Euros), since the tests also show that some products might have CRI values that do not comply with EU legislation. Also total power and standby power can easily be measured by retailers who wish to provide better consumer information. Quality power meters are around 300 Euros, and even some new power meters for only 30 Euros can perform precise measurements as well, though those must be tested to verify good performance[4].

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The Next Wave in Residential Lighting Market Transformation: The Role of LEDs and LED Fixtures

K. H. Tiedemann and I. M. Sulyma

BC Hydro and Research 4 Results

Abstract

CFL incentive programs have been the cornerstone of residential energy efficiency programs in North America, and they have provided cost effective savings and encouraged residential customer to move beyond reliance on energy inefficient incandescent and halogen lamps. The next wave in residential lighting programs includes LED lamps and LED fixtures which have higher lumen output per watt than CFLs and CFL fixtures. From 2011 through 2014 (fiscal years F2012-F2015), BC Hydro's Energy Star Lighting program provided financial incentives, information and marketing support to build the domestic market for LEDs and LED fixtures, as well as other energy efficient lamps and fixtures. This study provides an impact and market evaluation of the impact of the Energy Efficient Lighting program. This study includes a program review, a supply-side assessment, a demand-side assessment, analysis of lighting hours of use, and evaluation of energy and peak demand savings.

Introduction

In many North American jurisdictions, residential lighting programs represent a significant share of electricity conservation or demand side management (DSM) savings. To date, most of these savings have come from the promotion of purchase and installation of standard twister or spiral CFLs. As a significant degree of market transformation has been achieved with standard CFLs replacing incandescent lamps, a number of utilities and other DSM implementing agencies have reduced or eliminated incentives for standard CFLs, and they have instead provide support for purchase and installation of specialty CFLs including reflectors, A-lamps, globes and dimmable lamps; Energy Star lighting fixtures; and LEDs. Most recently, white LEDs have been recommended for general use because of high and improving efficiency in terms of lumens per watt, substantial improvements in light quality in terms of colour temperature, long lamp life and low life cycle costs. Residential lighting programs in North America have emphasized four main delivery mechanisms. (1) Upstream Buy-Down. Upstream buy-downs involve incentives to manufactures to have the retailers mark down the cost of qualifying energy efficient lights and fixtures at the time of purchase. (2) Direct Installation. Direct installation typically involves the direct installation of CFLs at the time of a residential audit. (3) Downstream Buy-Down. Downstream buy-downs typically involve point-of-sale or mail-in coupons to obtain the product at a discounted price. (4) Give Away. Give away typically involves provision of free CFLs at promotional events or through the mail. The large and growing literature on energy efficient residential lighting includes [1]-[17].

This report provides an evaluation of the impacts and effects of BC Hydro's Residential Lighting program. BC Hydro's Residential Lighting program is a multi-year energy acquisition and market transformation initiative that encourages its customers to use energy-efficient lighting, with a focus on compact fluorescent lamps (CFLs), light emitting diodes (LEDs), Energy Star fixtures and LED fixtures. The objectives of the program include: (1) sustain and increase a greater market share in advance of regulations for more efficient lighting; (2) promote efficient lighting products not covered by regulations and newer products such as LEDs; (3) promote and increase awareness province-wide and drive customers to retailers to purchase efficient products; and (4) provide residents province-wide with an accessible and simple lighting program.

To earn the Energy Star label, manufacturers must certify that the product meets the energy efficiency criteria set by Natural Resources Canada, the US Environmental Protection Agency and the US Department of Energy. When products are certified to meet these energy efficiency standards, the manufacturers may place the Energy Star label on their lighting products. As technology advances and more energy-efficient lighting products are available in the marketplace, Energy Star reviews the guidelines for the lighting category and strengthens them as necessary to ensure that generally only the top 25% of lighting products in terms of energy efficiency can earn the Energy Star label. BC Hydro's Residential Lighting program has gone through five phases, with each phase building on the success of previous work while focussing on emerging energy efficient lighting technologies including both lamps and fixtures.

Phase 1: March 2002-August 2004. The program was launched in March 2002, with an initial focus on building awareness and interest in CFLs. The pilot CFL initiative was launched in the communities of Courtenay, Comox and Quesnel. Bulk CFL purchases were made by BC Hydro and distributed free to customers using redeemable coupons at retail partners. The pilot CFL program was expanded to the remainder of Vancouver Island, reflecting a desire to slow load growth in response to transmission constraints. An initial CFL torchiere campaign provided incentive coupons to encourage customers to purchase CFL torchieres rather than halogen torchieres.

Phase 2: October 2004-December 2005. The Fall Lighting Campaign in 2004 included mail in coupons and in-store exchange events focussing on CFLs, seasonal LEDs (SLEDs) and CFL torchieres. This lighting campaign introduced two-tiered rebates to encourage purchases of the most efficient lighting products. The Energy Star Fixtures program was introduced to motivate customers to switch from halogen and incandescent technologies to Energy Star lighting fixtures.

Phase 3: October 2006-April 2007. Fall campaign in 2006 used in-store coupons and point of sales marketing. Participating Energy Star fixture retailers were classified as silver or gold depending on their level of support; at silver retailers, mail-in rebate coupons were available for purchase of qualifying product; at gold retailers, there was a wide range of promotional activities including in-store events, and a Prius vehicle draw.

Phase 4: June 2007-June 2011. The CFL program component began a transition from spirals to specialty bulbs. CFL coupons were replaced by instant in-store discounts and manufacture buy-downs, with an increased focus on non-incentive promotional activities including advertising and in-store events.

Phase 5: July 2011-June 2014. Increased focus was placed on promotion of specialty CFLs, LEDs, Energy Star fixtures and LED fixtures. Instant in-store discounts and manufacturer buy-downs continued to be offered. Provincial minimum energy performance standards for 75W-100W General Service A type lamps came into force in January 2011. New major retail partners were added to increase market penetration of energy efficient lighting technologies.

Method

This study approach used multiple lines of evidence, since no single line of evidence provided information on all of the evaluation issues.

Program Review. To conduct the program review and develop the program logic model, we reviewed program documents, interviewed BC Hydro program staff, and conducted a literature review focussing on recent studies and reports of residential DSM lighting programs in other jurisdictions.

Supply-Side Assessment. To undertake the supply-side assessment, we tabulated and examined relevant results of the annual in-store surveys of lighting stocking behaviour in representative samples of retail stores and examined trends. These surveys had about 40 participants per year. In addition, a trade ally survey was undertaken with a sample of nine buyers and managers of major retail chains.

Demand-Side Assessment. To undertake the demand-side assessment, we tabulated and compared results of two F2013 residential customer lighting surveys using z-test for differences. The BC survey had 602 respondents and the North and South Dakotas survey had 450 respondents.

Hours of Use and Peak. To measure hours of use and peak, we conducted an in-home monitoring program of 333 lighting fixtures with each fixture monitored for a minimum of 12 months.

Energy and Demand Savings. To estimate demand and energy savings, we used detailed engineering algorithms.

Results

Program Review

BC Hydro's Residential Lighting program was an energy acquisition and market transformation program targeted at both residential consumers of lighting products and supply-side actors including manufacturers, distributors and retailers. The objectives of the program included: (1) sustain and increase a greater market share in advance of regulations for more efficient lighting; (2) promote efficient lighting products not covered by regulations and newer products such as LEDs; (3) promote and increase awareness province wide and drive customers to retailers to purchase efficient products; and (4) provide residents province-wide with an accessible and simple lighting program.

At the time of program launch of the program in June 2010, market analysis indicated that although considerable progress had been made in transforming the residential lighting market, there were still barriers to achieving higher penetration for advanced lighting products including specialty CFLs, LEDs and energy efficient fixtures. From a program logic perspective, there were three main program activities: retailer education, product rebates and consumer education. (1) Power Smart has provided retailer education for the residential lighting market since the inception of the program. Retailer education was a key component of the Residential Lighting program, and retailer education was conducted both on-site at stores and on-line. (2) Product rebates were aimed at creating customer interest in energy efficient lighting and reducing first costs. Spring and Fall Lighting Campaigns included in-store instant discounts on selected lighting products. (3) Consumer education was aimed at creating customer awareness of energy efficient lighting products, and increasing knowledge and purchase intent for energy efficiency lighting products, and the lighting campaigns included radio, print, television advertising and point of purchase materials.

A key aspect of the program review was an assessment of the program rationale, in other words, does the program make sense? Program rationale can be assessed in a variety of ways, but the most straight forward way is to build a program logic model. A program logic model divides a program into its main activities, and then examines the logic chain of inputs, outputs, purpose and goal for each activity. The following table provides a program logic model focussing on input, output, purpose and goal statements for each of the three main activities, and then and describes key assumptions which must be met for the program to be effective. The program rationale was examined using this program logic model, which was developed from interviews with staff, a documents review and a literature review. This review and analysis confirmed that the basic program logic was valid. There were strong linkages among inputs, outputs, purposes and goal statements. Indicators for key components of the logic model were clear, well defined and measurable.

Table 1. Program Logic Model

	Retailer education	**Product Rebates**	**Consumer education**	**Assumptions**
Inputs	Retailer staff training conducted	Power Smart and manufacturer rebates in place	Advertising, promotions and point of purchase material provided	Suitable inventory of advanced lighting products available in stores
Outputs	Increased sales person knowledge of energy efficiency	Reduce first cost of energy efficient lighting products	Increased customer knowledge and awareness of energy efficiency	Energy efficient lighting meets customers' lighting requirements
Purpose	Increased sales of energy efficient lamps by 679,000 units and energy efficient fixtures by 186,000 units by the end of F2014			Rebound is negligible
Goal	Save 41 GWh of energy per year by the end of F2014			-

Supply-side Assessment

The purpose of the supply-side assessment was to examine product shelf space share, product prices, and product wattages for lamps and fixtures. The main data source was a series of in-store shelf stock surveys, typically with n = 40 stores per year. Lighting shelf stock surveys have been conducted by Power Smart for ten years, but earlier surveys focused almost entirely on CFLs, and comprehensive information is available for only the most recent surveys.

For purposes of the analysis, it was necessary to have a basis of comparison for various types of lamps. The following table places lamps into categories with similar light output in lumens, and it uses this as the basis for defining wattages with similar light output.

Table 2. Equivalent Wattages (W)

Incandescent	CFL	LED	Halogen
40	8-12	4-5	40
60	13-18	6-8	60
75	18-22	9-13	75
100	23-30	16-20	100
150	30-55	25-28	150

Note. Halogen lamps are about 10% to 20% more efficient than regular incandescent lamps, but since they tend to have the same range of wattages as regular incandescent lamps, we have assumed that most purchasers would choose between the same wattages for incandescent and halogen lamps.

Table 3 shows trends in shelf stock shares by fiscal year for standard base lamps and for fixtures. For these five years, the shelf stock shares by lamp type have changed substantially. In particular, the share of incandescent lamps fell from 61% in F2010 to 43% in F2014, while the share of LEDs rose from just 4% in F2010 to 15% in F2014.

Table 3. Lamp and Fixture Shelf Stock Shares (%)

	F2010	F20011	F2012	F2013	F2014
Lamps					
Incandescent	61	61	60	47	43
CFL	23	24	24	25	25
LED	4	3	4	10	15
Halogen	12	12	12	18	17
Total	100	100	100	100	100
Fixtures					
Energy Star	6	8	7	7	6
Other	94	92	93	93	94
Total	100	100	100	100	100

Table 4 shows trends in prices for representative lamps and fixtures. From F2010 to F2014, 60 watt incandescent lamps and standard/A19 LEDs have fallen in price, while 13 watt spiral CFLs and reflector/par halogen lamps have risen in price.

Table 4. Representative Lamp and Fixture Prices (dollars per lamp or fixture)

	Type	F2010	F20011	F2012	F2013	F2014
Lamps						
Incandescent	60 W	1.16	0.85	1.10	1.11	1.07
CFL	13 W spiral	3.43	3.59	3.90	3.81	3.81
LED	Standard/A19	24.92	24.63	24.34	22.22	18.34
Halogen	Reflector/PAR	7.10	6.99	6.89	6.79	7.43
Fixtures						
Energy Star	Ceiling fixtures	28.91	32.44	39.66	40.44	45.45

Demand-side Assessment.

The purpose of the demand-side analysis was to examine customer product awareness, lamp purchase behaviour, lamp installation behaviour, lamp storage behaviour, lamp replacement behaviour, customer satisfaction and program attribution of energy savings for six product categories – five lamp categories and one lamp category. The main data sources were surveys of BC Hydro residential customers (n = 602) and North and of South Dakota residential customers (n = 450). North and South Dakota were initially chosen as the comparison region because they had demographic characteristics quite similar to those of British Columbia, but did not have significant utility DSM programs for energy efficient lamps.

Survey respondents were asked about whether or not they were aware of various lighting products, and Table 5 shows the survey results for lighting product awareness. BC survey respondents show a higher level of awareness than Dakota survey respondents for LEDs, halogens, Energy Star fixtures and LED fixtures. Dakota survey respondents show a higher level of awareness than BC survey respondents for incandescent lamps and CFLs.

Table 5. Product Awareness F2013 (%)

	BC (n = 602)	Dakotas (n = 450)	Difference	Z-test	Significance
Lamps					
Incandescent	93	95	-2	-1.42	0.08
CFL	88	89	-1	-0.44	0.33
LED	73	66	7	2.45	0.01
Halogen	81	78	3	1.20	0.12
Fixtures					
Energy Star	33	32	1	0.34	0.37
LED	51	48	3	0.96	0.17

Survey respondents were asked whether they recalled seeing any information, advertising or promotions for CFLs or LEDs. The results are shown in Table 6. Positive responses were significantly higher in British Columbia than the Dakotas.

Table 6. Recall Information, Advertising or Promotions F2013 (%)

	BC	Dakotas	Difference	Z-test	Significance
Lamps					
CFL	46	34	12	3.92	<0.0001
LED	26	10	16	6.52	<0.0001

Survey respondents were asked whether or not they had purchased various lighting products, and Table 7 shows the survey results for lighting product purchases. BC survey respondents show a higher level of purchase than Dakota survey respondents for three of the product categories. Dakota survey respondents show a higher level of purchase than BC survey respondents for incandescent lamps and Energy Star fixtures.

Table 7. Purchased at Least One F2013 (%)

	BC	Dakotas	Difference	Z-test	Significance
Lamps					
Incandescent	41	46	-5	-1.62	0.05
CFL	40	39	1	0.36	0.35
LED	14	7	7	3.52	0.0002
Halogen	23	14	10	3.67	0.0001
Fixtures					
Energy Star	2	3	-1	-1.15	0.13

Survey respondents were asked whether or not they had installed various types of lighting products, and Table 8 shows the survey results for lighting product installation. BC survey respondents show a higher level of product installation than Dakota survey respondents for three of the six product categories. Dakota survey respondents show a higher level of product installation than BC survey respondents for incandescent lamps and Energy Star fixtures.

Table 8. Installed at Least One F2013 (%)

	BC	Dakotas	Difference	Z-test	Significance
Lamps					
Incandescent	58	65	-7	-2.26	0.01
CFL	58	56	2	0.065	0.26
LED	16	7	9	4.36	<0.0001
Halogen	29	16	13	4.92	<0.0001
Fixtures					
Energy Star	2	3	-1	-1.15	0.13

Survey respondents were asked how satisfied they were with specialty CFL and LED lamps. Table 9 shows the proportion of survey respondents who indicated that they were very satisfied.

Table 9. Very Satisfied with Lamps F2013 (%)

	BC	Dakotas	Difference	Z-test	Significance
Lamps					
Specialty CFL	33	41	-8	-2.70	0.003
LED	69	59	10	3.39	0.003

To understand the longer-term impact of the program we built an econometric demand model for BC using annual estimates of residential saturation of energy efficient lamps and prices of energy efficient lamps, as well as awareness of energy efficient lamps and a dummy variable for the Energy Star program period. Both ordinary least squares (OLS) and maximum likelihood (ML) models were estimated. The regression results are shown in Table 10. The estimated models perform well with very high adjusted R-squared and minimal auto-correlation. One, two or three asterisks indicate that the coefficient is significant at the 10%, 5% or 1% level respectively.

Table 10. Demand for Energy Efficient Lamps (log of average installed)

	OLS		**ML**	
	Coefficient	St. dev.	Coefficient	St. dev.
Constant	3.12***	-0.66	3.19***	0.63
Log of price	-1.52***	0.29	-1.55***	0.27
Log of awareness	1.57*	0.72	1.55**	0.67
Program dummy	1.04***	0.29	1.10***	0.28
Adjusted R-sq.	0.99	-	0.99	-
Durbin-Watson	1.89	0.05	2.11	-0.05

Because the regression models are in double log form, the regression coefficients are elasticities, except for the program period dummy variable which needs to be rescaled. Table 11 shows the elasticities based on the demand regression models. These elasticities say that a 1% increase in price reduces saturation of energy efficient lamps by 1.52% to 1.55%, a 1% increase in customer awareness of energy efficient lamps increases saturation of energy efficient lamps by 1.57% to 1.55%, and the presence of the Energy Star Lighting program increases saturation of energy efficient lamps by 175% to 183%.

Table 11. Elasticities (%)

	OLS	ML
Price	-1.52	-1.55
Awareness	1.57	1.55
Program	183.0	175.0

Note. For price and awareness the elasticity is the percentage change due to a one percent in the forcing variable, but for program the elasticity is the percentage change due to the presence of the Energy Star Lighting program.

Hours of Use and Peak Coincidence.

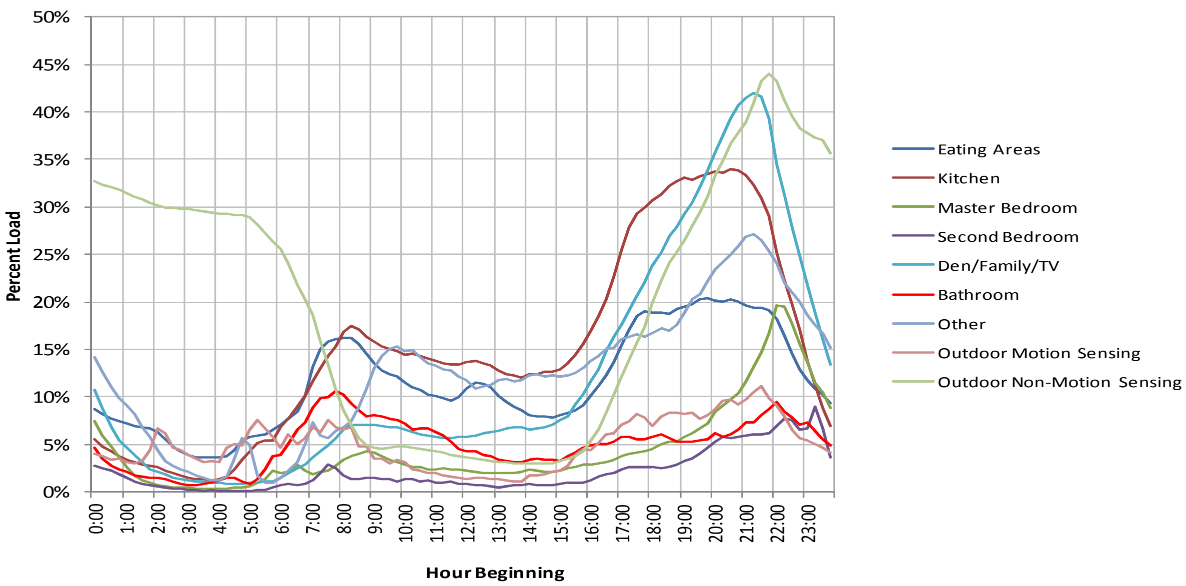
The purpose of the hours of use and peak analysis was to determine annual, seasonal and daily operating hours of use for light fixtures located in different areas of the home. Information collected through the monitoring study was used to estimate annual hours of use and peak coincidence. Lighting end uses (n = 333) were monitored using time of use loggers between June 2010 and July 2011, so that at least 12 months of data was collected for each monitored lamp. Figure 1 shows the average daily load shapes by room.

Information on location of lamps and fixtures by room was used to weight the monitored hours of use by room to calculate weighted hours of use and peak for lamps and for fixtures. The results of these calculations are shown in Table 12.

Table 12. Hours of Use and Peak Coincidence

	Average hours of use	Peak coincidence
Lamps	2.56	0.31
Fixtures	3.18	0.39

Figure 1. Daily Lighting Load Shapes



Energy and Peak Savings.

The purpose of the impact analysis was to estimate the program impact on energy and peak demand savings for CFLs, LEDs, Energy Star fixtures and LED fixtures. Key parameters were the difference in watts between the base and the efficient technology, annual hours of use, the peak coincidence rate, the installation rate net of replacements, the free rider, the spillover rate, the electricity cross effects adjustment, and the number of rebated units.

For energy savings, the basic algorithm was:

$\Delta GWh = \Delta W \cdot Hours \cdot Install \cdot (1 - FR + SO) \cdot (1 - CE) \cdot Units.$

For peak demand savings, the basic algorithm was:

$\Delta MW = \Delta W \cdot Peak\ Coincidence \cdot Install \cdot (1 - FR + SO) \cdot (1 - CE) \cdot Units.$

The following table summarizes energy savings for the period F2012 through F2015. Please note that F2015 included only three months because the Residential Lighting program was completed, although BC Hydro continued to support and promote LEDs and LED fixtures through a new residential energy efficiency program. Energy savings from LED lamps and fixtures rose from 16.2 GWh/y in F2012 to 34.5 GWh/y in F2015.

Table 13. Energy Savings (GWh/y)

	F2012	F2013	F2014	F2015
CFL	8.5	5.7	1.3	-
LED	15.6	44.0	37.8	34.0
LED fixtures	0.6	0.9	0.5	0.5
ES fixtures	4.0	2.2	0.2	0.1
Total	28.7	52.8	39.8	34.6

The following table summarizes peak demand savings for the period F2012 through F2015. Peak demand savings from LED lamps and fixtures rose from 5.3 MW in F2012 to 11.5 MW in F2015.

Table 14. Peak Demand Savings (GWh/y)

	F2012	F2013	F2014	F2015
CFL	2.8	1.9	0.4	-
LED	5.1	14.6	12.5	11.3
LED fixtures	0.2	0.3	0.2	0.2
ES fixtures	1.4	0.7	0.1	0.0
Total	9.5	17.5	13.2	11.5

Conclusions

Study Purpose. From 2011 through 2014 (fiscal years F2012-F2015), BC Hydro's Energy Star Lighting program provided financial incentives, information and marketing support to build the domestic market for LEDs and LED fixtures, as well as other energy efficient lamps and fixtures. This study provides an impact and market evaluation of the impact of BC Hydro's Energy Efficient Lighting program. This study includes a program review, a supply-side assessment, a demand-side assessment, analysis of lighting hours of use, and evaluation of energy and peak demand savings.

Program Design and Implementation. Since the launch of Power Smart's Energy Residential Program, there has been a significant degree of lighting market transformation as many incandescent lamps have been replaced with spiral CFLs, and the program has moved on from its initial focus on spiral CFLs to a wider range of energy efficient lighting products. The program has continued to evolve in response to changes in the market, and it now successfully features a wide range of energy efficient lighting products including specialty CFLs, LEDs, Energy Star fixtures and LED fixtures. Evidence suggests that the program is having a significant impact on the sales of LED lamps.

Program Energy and Peak Impacts. Engineering algorithms informed by BC Hydro customer survey data, North and South Dakota customer survey data, and on-site metering data were used to estimate program impacts. Customer surveys found significant evidence of market effects for LEDs. Evaluated energy savings were 28.7 GWh in F2012, 52.8 GWh in F2013, 39.8 GWh in F2014 and 34.6 GWh in F2015. Evaluated peak demand savings were 9.5 MW in F2012, 17.5 MW in F2013, 13.2 MW in F2014 and 11.5 MW in F2015.

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Static Scalar Swarm Algorithms for Lighting

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Abstract

Since a sizeable amount of electrical power is consumed by lighting, saving energy in this field is important to reach the goals of the energy transition. Using LED lamps contributes an essential amount of savings. Even more energy can be saved by illuminating only when, where and as much as necessary.

Lighting systems consist of an array of lamps. An on-demand and good-enough lighting at each working place can be realized by equipping each lamp with light and presence sensors, by adding intelligence and communication abilities to them and by using suitable control algorithms. Since the proposed setup has similarities with a swarm, swarm optimization algorithms are potentially good candidates. Further a decentralized swarm setup has the advantage of low hardware requirements and no central controller is needed.

We evaluated swarm algorithms regarding energy savings and user comfort. Based on the rules for swarm algorithms we designed various swarm algorithms and simulated their illumination control. We compared these swarm algorithms with conventional approaches. The results of the simulations were evaluated regarding the energy consumption and how accurate and constant the illumination is.

The linear optimization algorithm showed the best results concerning energy consumption and stability. The investigated swarm algorithms tended to be less stable and predictable. Linear optimization requires a central processing unit with considerable computational power however, which might make the retrofit of existing installation impractical. Therefore further work is necessary to improve the stability of the swarm algorithms and to verify the simulation results in a test setup.

Introduction

The amount of electrical power consumed for lighting is not negligible. The total electrical energy consumption in Switzerland is about 59.9 TWh/a (2010). 14% (8.3 TWh/a) thereof is consumed by lighting where public, industrial and commercial buildings contribute with 10% (5.9 TWh/a) and private buildings with 4% (2.4 TWh/a) [1].

In [1], it is estimated that the consumption will increase until 2035 up to 71.8 TWh/a. Then the percentage of lighting will be 13% (9.2 TWh/a) with public, industrial and commercial buildings contributing 9% (6.5 TWh/a) and private buildings 4% (2.7 TWh/a). This extrapolation is based on the population development and the increasing needs of consumers.

With respect to technological developments, the author of [1] predicts a potential for electrical energy saving for lighting of 40% in public, industrial and commercial buildings whereas the potential is 60% in private buildings. Main reason for this saving is due to the technological development, particularly the change from incandescent lamps to LED – technology. Further potential offers the use of intelligent control of lighting: light only when and where and in the amount it is needed.

Currently, there are two types of products on market that make first step into the direction of intelligent control of lighting. The simpler systems are stand-alone products that often combine an occupancy sensor with an illuminance sensor and an actor to control a light. Thereby, one occupancy sensor is mostly used to control a number of lights, e.g. all the lamps in a room. A setup with one such occupancy sensor per light is rarely used on one hand for cost reasons and on the other hand because each occupancy sensor works independently from the others which can be uncomfortable because the surrounding of the person will be dark. Particularly when walking, it's like walking against a dark wall.

The currently available complex lighting systems, so called lighting control systems, consist of a network of connected devices like sensors (occupancy) and actors (switches). The connection can be hardwired or wireless and is based on a uniform communication protocol such as. KNX, DMX, DALI. Hardwired communication systems need cables that have to be installed on top of power cables. That could be eliminated by the use of wireless technology like for example ZigBee, Bluetooth, WLAN or 6LoWPAN. Both cases are however realized with a central managing unit. The information of the sensors is processed by the central unit which then controls the lights using the actors. With such systems the comfort can be augmented by not only switching on the lights where people are present but also to dim the surrounding lights a little bit.

In this paper we will look at a system where the sensors for occupancy and illumination are integrated into the lamp. Additionally a microprocessor is built in to control the light depending on the sensor signals. The lamp is equipped with means for wireless communication. Therefore a lamp can control the light also dependent on other lamps. There is no need to install cables or to have a central unit. Such a lamp can be seen as an individual of a swarm and using swarm optimization algorithms allows the use of microprocessors with low power and low resources. The behaviour of a swarm can be more complex than the behaviour of its individuals. With the approach of swarm optimization we pursued mainly two goals: 1. lower the energy consumption of a lighting system and 2. an accepted comfort for the users. As the sensors and the processor are integrated into the lamp there is no need for further installations. This solution helps in retrofit situations: only the lamps have to be exchanged.

In the next chapter, the investigated swarm algorithms are described in detail. We also introduce the simulation tool that was used to assess the various algorithms. The corresponding results and discussion are provided in the following chapter.

They show that the best results concerning energy consumption and stability are obtained by linear optimization that was used as a baseline. Swarm optimization algorithms are still promising with regards to energy consumption but lack in stability and predictability. Further work needs to be done to improve the swarm optimization algorithms and to verify the obtained simulation results in a test setup. A motivation for the additional work is that solutions with a central processing unit are impractical for retrofitting.

Swarm algorithms: a new approach for lighting control

To address energy consumption, user comfort and easy retrofitting the idea of using swarm algorithms for lighting control was pursued. We look at every lamp being a single individual of a swarm. There is no central management unit like a building automation system or a server that controls the lighting. But every lamp communicates with the neighbours to optimize the illuminance and energy consumption. This approach doesn't need high performance computers in each individual.

Goals

For a lighting system – particularly in public, industrial and commercial buildings – we prosecute two main goals:

- Energy saving
- Accepted comfort (minimal illuminance of 500 lux for office work places, low variation in illuminance)

Energy saving

Energy saving in lighting system can be achieved by change of technology of the illuminant. Changing to LED results in a potential in energy savings from 60% (compared to fluorescent tubes) up to 90% (compared to incandescent lamp).

Further savings can be realized by controlling the lighting. Many a time in a room every lamp is switched on although it's not necessary because at certain places there is no person. Therefore the system shall only illuminate when it is needed (not sufficient natural light) and where it is needed (presence of people). It is aimed to save up to 50% energy by controlling the lamps dependent on illuminance and presence compared to a lighting system without a controlling system.

Comfort

The illumination at a person's location must have a value according to the appropriate standards. For an office work place the illumination shall reach at least 500 lux.

If lighting is controlled only considering existing illuminance and presence of people this can lead to uncomfortable situations: the place where people is located is illuminated according to the requirements but the surrounding areas are dark. Particularly if a person is walking along a corridor this feels like walking against a dark wall.
Therefore the controlling system has to illuminate the neighbouring areas of the location of people as well but with less luminosity.

Another aspect of comfort is the variance in luminosity. As described in [2] constant light and slowly varying light (period more than 5 min) is accepted well. This is also valid if the frequency of variation is higher than 30 Hz. Light variations between 0.67 and 18 Hz are perceived as most distracting. Therefore a lighting system has to regulate the light in a way that it doesn't produce varying light with periods shorter than 5 min, except when conditions change like a person entering a room.

Swarm Algorithms

Generally spoken an individual in a swarm acts depending on what it perceives from the environment. The environment can be both: a dangerous situation like an obstacle or a predator where the individual has to pass around or the behaviour of neighbouring individuals which influences the own behaviour. Two approaches to swarm algorithms that seem suitable for lighting control are particle swarm optimization and boids, see e.g. [3][4][5][6] and references within.

Particle Swarm Optimization

Particle Swarms are used to solve optimization problems. The lighting system can be seen as an optimization problem with the goal to reach the lowest possible energy consumption with an illumination considering the comfort of the users. Particle swarms realize the optimization by comparing the value to optimize at current location against the individuals and the global best solution already computed. Therefore the lamps illuminance is controlled in a way that the energy consumption is as low as possible but also respects the before mentioned conditions of minimal illumination and comfort.

Particle swarms consist of particles moving around the search space. For a lighting system we have two kinds of space: 1. the spatial distribution of the luminaires and 2. the value (in our case the energy consumption) to search an optimum for. Neighbours are defined through the spatial distribution not through proximity in search space. The particles (luminaires) that are spatial close are neighbours.

In our further investigation we use as the fitness function the energy consumption that shall be minimized. For simplicity we assume that energy consumption is proportional to the brightness of the light and that the brightness is controlled by a dim factor df. The fitness function becomes a scalar function:

$$\text{(1)} \qquad fitness = f(df)$$

Each particle calculates its dim factor df as

$$\text{(2)} \qquad df(t+1) = df(t) + dr(t+1)$$

where dr represents the velocity. The velocity in this case is the rate at which the dim factor is changed and we call it dim rate. The dim rate is calculated as

$$\text{(3)} \qquad dr(t+1) = dr(t) + c_1 * r_1(t)[df_{best}(t) - df(t)] + c_2 * r_2(t)\left[\widehat{df}_{best}(t) - df(t)\right]$$

Here dfbest is the best dim factor the particle has found since the first time step and $\widehat{\mathrm{df}}_{\mathrm{best}}$ is the best dim factor the particles neighbours have found since the first time step, c1 and c2 are acceleration constants that define the contribution of the cognitive and social components, and r1(t), r2(t) are random values to introduce a stochastic behaviour. The dim rate is set to fixed values when a light detects presence or absence respectively. This is necessary to get the particle accelerated to find a new optimum for the new conditions.

For stability reasons we damp the two acceleration constants with a factor d over time when the conditions are static. This is the case when people don't move around. The accelerations constants are reset to the initial values if conditions change, e.g. when people start moving.

$$(4) \qquad c_i(t+1) = c_i(t) * d$$

Using these equation leads to dim factors with value 0 what is equivalent to the lowest possible energy consumption. But then the condition of having enough illuminance at the place where a person stays is not fulfilled. Therefore a penalty function is introduced:

$$(5) \qquad penalty = f(illuminance, presence, df)$$

If presence is detected the penalty is higher the less illuminance we have. We also get a higher penalty if the illuminance is higher than the desired value of 500 lux.

Boids

Boids have been developed by Reynolds [6] and can explain the behaviour of bird flocks or fish schools. Boids base on three simple rules: Cohesion (move with the same speed as the others), Adhesion (move towards the centre of the others) and Separation (avoid collision with others). These three rules lead to a swarm that seems to be a single organism. For a lighting system the boids concept can be adapted so that lamps brightness depends on the brightness of the neighbours (Adhesion). The dim factor then is calculated according to (6) where $\mathrm{df}_{\mathrm{avg}}$ is the average dim factor of the neighbouring luminaires that detected presence of people.

$$(6) \qquad df(t+1) = \begin{cases} df(t) + dr(t); & if\ df(t) < df_{avg}(t) \\ df(t) - dr(t); & if\ df(t) \geq df_{avg}(t) \end{cases}$$

The speed of change in brightness represented by the dim rate dr can be directed towards the average dim rate of the neighbours (Cohesion):

$$(7) \qquad dr(t+1) = \frac{1}{n} \sum_{i=1}^{n} dr_i(t)$$

We have not implemented the rule for separation. It's no problem when two individuals have the same dim factor. But we have introduced an additional rule that respects presence of people. In this case the minimal required illuminance must be reached and therefore the algorithm has to increase the dim factor with a higher dim rate dr:

$$(8) \qquad dr(t+1) = 2 * dr(t)$$

Simple Swarm

We also implemented a very simple algorithm where the dim factor of an individual is calculated depending on the illuminance and the presence of people. Only when no presence is detected the dim factor will depend on the neighbouring individuals that have detected presence.

$$(9) \qquad df(t+1) = \begin{cases} f(illuminance); & if\ presence\ detected \\ df_{avg}(t); & if\ no\ presence\ detected \end{cases}$$

Linear Optimization

To compare the results of the swarm optimization we use linear optimization. We search the minimum for the sum of dim factors of all luminaires:

$$(10) \qquad min\{c^T df | A * df \geq b, 0 \leq df \leq 1\}$$

where df represents a vector with the dim factors of each luminaire (to be determined), A is a vector of a conversion factor between dim factor and resulting illuminance of the luminaire and b is a vector of the constraints. For each luminaire b is determined in dependence of the presence of a person; it is 500 lux in case of presence, 0 else. c is a vector where each element has the value 1.

Simulation

For the simulation of a lighting system a room with 24 lamps was chosen. The layout of the room is shown in Figure 1. Here also the path a person is walking through the room can be seen.

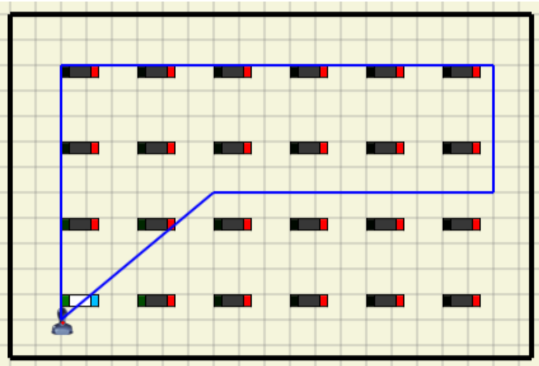

Figure 1: The layout of the simulated room with the path of a moving person

During a simulation that covers 55 seconds the person walks along the defined path. The dim factor of each lamp is calculated according to the chosen algorithm described in the previous chapter. The results of the simulation are the overall energy consumption and the illuminance at the location of the person walking through the room. The algorithms are then compared using these criteria:

1) energy consumption of all luminaires in the room
2) illuminance at the person's location
3) illuminance variability at the person's location

Concerning the energy consumption the best algorithm is that with the lowest energy consumption. We also compare it to a situation when all the luminaires are switched on all over the time. This comparison indicates the potential of energy savings compared to switch the luminaires manually. The luminaires have a standby power of 8 W with dim factor 0 and a maximum power of 146 W with the dim factor 1. In the case all luminaires are switched on the power consumption is

$$(11) \qquad P_{total,manual} = n_{luminaires} * P_{luminaire} = 24 * 146W = 3504\ W$$

The energy consumption during one simulation period of 55 seconds therefore is

$$(12) \qquad E_{total,manual} = P_{total,manual} * t_{simulationperiod} = 3504\ W * 55\ s = 192720\ Ws$$

The simulated illuminance is compared to the minimal required illuminance for an office work place of 500 lux. For the illuminance variability we look at the standard deviation of illuminance.

Results

The results of using swarm algorithms for a lighting controlling system have been compared to conventional algorithms. As relevant results with respect to the formulated goals, the energy consumption, the brightness at the persons location and the variation of brightness have been calculated in the simulation.

The results in Table 1 show the energy consumption, the illuminance and the variation of illuminance for the investigated lighting control algorithms.

Table 1: Energy consumption, illuminance and illuminance variability for the investigated lighting algorithms

Algorithm	Energy consumption [Ws]	Mean illuminance [lux]	Standard deviation of illuminance [lux]
Particle Swarm Optimization	40391	531	185
Boids	70857	530	126
Simple Swarm	60584	497	70
Linear optimization	39257	500	5

The swarm algorithms reach the nominal brightness quite good with the highest energy consumption and variation in brightness. The energy consumption can be explained by the fact that the lamps in the neighbourhood tend to have higher illuminance due to the algorithm.

The best result is obtained using a linear programming approach. This algorithm reaches the nominal brightness with the lowest energy consumption and the lowest variation of brightness.
Figure 2 gives an impression of the brightness over time for the algorithms. It clearly comes out that not all algorithms show a reasonable value of the variation of brightness. The illuminance obtained with linear optimization (LinOpt in Figure 2) shows the lowest variability whereas the particle swarm optimization (PSO in Figure 2) shows the highest variability regarding at the amplitude of the deviation from the nominal value.

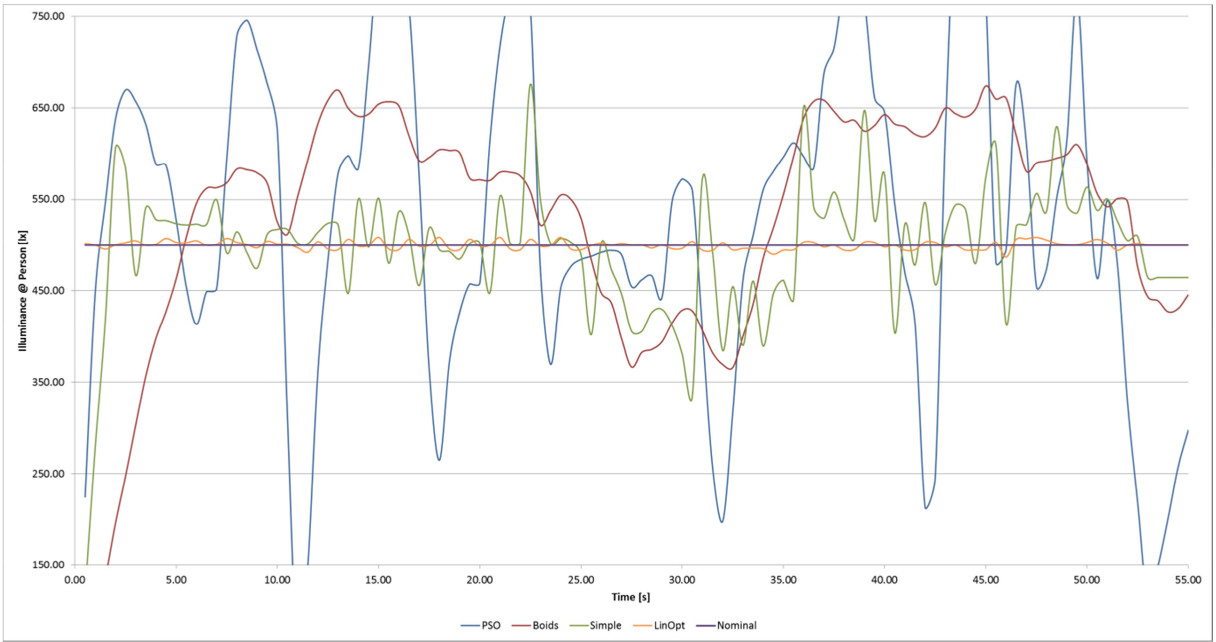

Figure 2: Comparison of the different algorithms where the illuminance at the person's location is shown over time

In

Table 2 the energy consumption of the investigated algorithms is compared to the energy consumption a full illuminance (all luminaires permanent on) has, see equation (12). The potential of energy saving using intelligent algorithms for lighting control can reach 80%.

Table 2: Energy consumption and potential of energy saving for the investigated lighting algorithms.

Algorithm	Energy consumption [Ws]	Energy saving [%]
Particle Swarm Optimization	40391	79
Boids	70857	63
Simple Swarm	60584	69
Linear optimization	39257	80

Conclusion

Swarm algorithms seem ideal candidates for lighting control due to the low system complexity compared to centrally controlled systems. In this work, various such algorithms have been assessed through simulation the main criteria being energy efficiency. Results indicate that the energy consumption of the investigated swarm algorithms is from equal up to 75% higher compared to the optimization approach using linear programming that was used as a benchmark. Brightness variations are likewise significantly higher for swarm algorithms. The average variation of the swarm algorithms is about 30 times higher than the variation of the linear optimization algorithm.

Outlook

The approach of using swarm algorithms for lighting systems seems promising due to the mentioned advantages. But as has been shown, further work is required to optimize their energy consumption and reduce the variation in brightness. More algorithms and the parameters of them will therefore be examined.
Till now we have worked with simulation data. In a next step the simulation results have to be verified in a real world installation of a lighting system. In such a setup, comfort aspects of the lighting algorithms should also be assessed. In particular, the local distribution of illuminance in a room should be looked at because it is expected that the feeling of comfort of a person can differ significantly depending on this distribution. The comfort feeling probably also is dependent on the activity of the person, like sitting at the table or walking along a corridor.

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Testing High Quality LED lamps for Residential Lighting in European Market: Results from PremiumLight project

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Abstract

The PremiuLight European project pursued the comprehensive testing of high efficiency lighting products. More than 330 lamps of 85 different types were tested during the project. Lamp types included 49 models of LED omnidirectional and candle-type lamps, 36 types of LED spots. All tested lamps, assumed to be "high quality" products, were purchased anonymously from store shelves in 12 participating European countries following a PremiumLight protocol detailed in the full paper. The product testing was carried out in 2 rounds (the first completed in April 2013 and the second completed in July 2014). Three independent laboratories in France, Sweden and Austria performed the measurements. Systematically measured lamp performance criteria include: luminous flux, luminous efficacy, correlated colour temperature, colour-rendering index, chromaticity difference, lamp spectrum, photometry and light flickering, absorbed power, EEI value, power factor and total harmonic distortion. These measurements were performed on new lamps without a "burn-in" period. Measured values were compared against manufacturer declarations.

Introduction - the PremiumLight project description and objectives

The EU regulations on Eco-design and Labelling for lighting provide an essential framework for supporting energy-efficient lighting solutions in the domestic sector. However, due to shortfalls regarding guidance of consumers towards high-quality energy-efficient lighting products, after the phase-out of the incandescent lamp many buyers were irritated and a generally negative attitude against energy saving lamps was observed. Thus supportive measures and consumer information services are required to support a smooth and effective transition from old inefficient lighting technology to highly efficient LED-lighting.

To support this goal the IEE-project PremiumLight[1] implemented a broad market-oriented action in twelve EU countries which was focused on the following measures:

- Making it easy for consumers to buy high-quality energy-efficient lighting products by providing comprehensive information services and tools to support product selection
- Enhancing promotion and visibility of high-quality energy-efficient products at the point of sale in cooperation with retailers
- Information on efficient high-quality lamp products by comprehensive product testing
- Broad dissemination of consumer-oriented information via media

The geographic region of the action covered 12 countries represented by Austrian Energy Agency (Austria), Berlin Energy Agency (Germany), SEVEn (Czech Republic), Politecnico Milano (Italy), Energy Saving Trust (UK), Energy Piano (Denmark), Motiva (Finland), University Toulouse 3

[1] www.premiumlight.eu

(France), EKODOMA (Latvia), ISR-University Coimbra (Portugal), Ecoserveis (Spain), TEM (Sweden).

The project included a strong cooperation with the retail sector as well as important stakeholders and others from the private and public service sectors. Cooperation with 65 retail chains or retailer groups was implemented in total supporting effective information of consumers with various tools at the point of sale have been proposed. In addition, several hundred stakeholders like municipalities, utilities, luminaire retailers and lighting manufacturers, lighting planners and installers were addressed and involved in different information measures. The end of the project has achieved this action in November 2015 but some partners are engaged to continue this collaboration at national level in the future.

Furthermore, a comprehensive series of product testing provided an important basis for the market-oriented action and included more than 95 lamp models from different brands. Product tests were mainly focused on new LED lamps (10 CFL models have been also analysed but this is out of the scope of the present paper).

The testing concept and lamp selection criteria

One central objective of the project was to provide with independent information on essential lamp performance criteria so that consumers can identify and purchase efficient, high-quality products. The new European Eco-Design-regulation for domestic lamps requires the mandatory declaration by manufacturers of a large number of quality, efficiency and performance criteria. PremiumLight, however, focused on lamp performance two product classes, namely LED omnidirectional lamps and LED spots. Testing results provide concrete essential consumer information on good products comprehensively fulfilling consumer needs in terms of quality, energy efficiency, environmental aspects etc. Testing results were included in all dissemination activities in the consortium and via key actors.

The PremiumLight project focused on high quality lighting products that were commonly available in the EU markets where they were purchased. For this purpose, the project developed criteria to define an efficient, high-quality lamp. The criteria were designed to cover the main product characteristics that are relevant and observable by the consumer. Several of these criteria have been defined earlier as for example by the Quality Charter for Solid-State Lighting [EQC-11] or the tier scheme proposed by the International Energy Agency 4E-SSL Annex[2]. Additionally, the eco-design regulations 244/2009 and 1194/2012 [EUR-09] [EUR-12] also recently established minimum standards. These minimum standards define the minimum requirements that must be met by any lamp that is sold on the EU-market today. The following aspects were considered for establishing PremiumLight criteria (Table 1 shows all criteria used for the anonymous selection of PremiumLight quality lamps for testing):

Lamp efficacy

The lamp efficacy describes how much light the lamp produces per watt of electric power. It is expressed in lumen per watt (lm/W). In the early days of LED technology efficacy was often measured for cold lamps under laboratory conditions. However, the efficacy of a lamp at 25°C is much higher than for lamps at typical operating temperatures. Today the most efficient lamps can reach more than 100 lm/W under real-life use conditions. The PremiumLight criteria established for LEDs for the purpose of the project were efficiency class A+ following EU Directive 92/75/EC calculation method based on the value of Energy Efficiency Index (EEI). It is not possible to give a single value in terms of associated luminous efficacy in lumens per watt because the EEI value differs for the various product categories.

Average Lifetime and Lumen maintenance

For LEDs intended for domestic lighting purposes, manufacturer declared lifespan ranges between 10,000 and 50,000 hours. It would take one or more years to test lamps to determine whether such declared lifespans are accurate. Therefore, this kind of testing is not helpful for the consumer, since

[2] http://ssl.iea-4e.org/

lamp models are typically replaced every few years. However, the useful lifetime of LEDs is not only defined by the total time until lamp failure but by the decrease of lumen output over time as well. When lamp lumen output has declined to 70% of the declared value the effectively useful lamp lifetime has been reached. Thus the lamp lifetime of LEDs is often declared by "$L_{70}B_{50}$" values, respectively the number of hours that it takes for at least 50% of the lamps to experience an at least 70% decline from the initial lumen output. Testing shall follow IEC/PAS 62612 Ed.1 [IEC-13] including a temperature cycling shock test and a supply voltage switching test with a number of cycles equal to half or all of the rated lamp life hours. A shorter lifetime of e.g. 15,000 hours might therefore be acceptable for LEDs in case they are sold at comparably low prices. The drawback of this is the fact that a low (15,000 h) lifespan determined by $L_{70}B_{50}$ may include a sample where 25% of the sample fails at 5,000 h and this of course not acceptable for high quality products. The PremiumLight quality suggests a lifetime of least 20,000 h for premium-quality LEDs.

Colour temperature

The colour temperature of a lamp indicates the appearance of white light that may range from yellowish warm white to bluish cold white. With reference to IEC/PAS 62612 Ed.1 [IEC-13], the Quality Charter [EQC-11] for Solid-State Lighting requires CCT (Correlated Colour Temperature) ratings for lamps for domestic use should be between F2700 (CCT=2,720 K, x=0,463 and y=0,420), F3000 (CCT=2,940 K, x=0.440 and y=0.403) or F3500 (CCT=3,450 K, x=0.409 and y=0.394). As indicated above, colour temperature is not a quality criterion. The selection of a specific colour temperature depends primarily on consumer preference. For household lighting in northern European countries warm white light with CCTs ranging from 2,700 K to 3,000 K are often preferred. However, it has been reported that in southern European countries in particular more neutral to cool white lamps with CCTs 5,000 K and above are often requested. A quality criterion however is the uniformity of the colour temperature for a specific lamp model, thus the deviation of the colour temperature from the declared values should be small. This is important to avoid visible colour variation in a multi-LED spots, lamps, or even luminaires. The focus of product testing in the PremiumLight project was put on warm white lamps, as this lamp type is more common in households.

Colour Rendering

The Colour Rendering Index (CRI) indicates how well the human eye can identify specific colours when illuminated by a specific lamp3. A CRI value of 100 is achieved by standardized daylight or by a black body (incandescent lamps are effectively close to blackbodies). Other light sources typically have lower CRI values. The eco-design regulation requires a minimum CRI of 80. The UK EST LED program required CRI > 85 in 2011 and CRI > 90 in 2012. Today there are already LED lamps available with a CRI between 90 and 95. PremiumLight set a minimum CRI selection criterion at 80.

Other issues

Another criterion that has been addressed by PremiumLight is the dimmability of LEDs. Dimmability is not a quality criterion and there are dimmable and non-dimmable lamp models on the market. Dimmability is also dependent on the type of dimmer used.

Additional criteria that have partly been tested in the PremiumLight project are flicker and power factor. These aspects are less easily checked by consumers since the relevant information is normally not provided on lamp packaging. LEDs may differ considerably regarding these two criteria. Thus some lamp models show strong flicker and low power factor whereas other lamps perform quite well.

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[3] CRI calculation method as proposed by CIE 13.3 [CIE-95]

Table 1: PremiumLight Quality Criteria

Parameter	LED bulb	LED spot	Comments
Minimum luminous efficacy [lm/W]	60	50	These values have been selected following previous market survey studies in Europe and USA (2011-12) and correspond to 10% best products
Minimum wattage [W] **Minimum luminous flux [lm]** **Minimum beam angle (°)**	8 470 -	4 - 20	When looking for LED-bulbs replacing GLS and halogens the lumen output value should be privileged (minimum 470 lm). For LED spots the luminous flux is not a discriminant criterion and beam aperture has to be taken into account. Beam angle is given by manufacturer and not tested in our laboratories
Minimum Energy Class	A+	A+	Calculation based on EEI value by using experimental luminous flux et input power values.
Minimum Colour Rendering Index	80	80	The actual definition of CRI is not fully applicable to LEDs.
Colour temperature range [K]	2,500-4,000	2,500-4,000	For domestic GLS replacement (warm white) a colour temperature of CCT<3000K is appropriate, however, for southern countries also CCT<4000K is acceptable.
Minimum Life span $L_{70}B_{50}$ [h] **Minimum number of switching cycles**	20,000 50,000	20,000 50,000	As given by manufacturer and not tested in our laboratories at this stage of the project. Ageing measurements are underway.

Measurement protocol and definitions

The PremiumLight project measured the following properties / quantities and compared them to manufacturers' declarations.

- RMS Voltage (V) and Current (A)
- Electrical input power (W)
- Power factor – PF and cosφ
- Total luminous flux (lm)
- Luminous efficacy (lm/W)
- Correlated Colour Temperature - CCT (K)
- Colour Rendering Index – CRI
- Chromaticity difference – $\Delta u'v'$
- Light Flicker percentage (%)

Power factor, chromaticity difference and Light Flicker Percentage were included as an option for all products as they were defined to be important for Europe. Manufacturers do not usually declare these values.

All laboratories involved in the project used the IEA 4E SSL Annex Test Method version 1.0 [IEA-13]. This Test Method includes the strictest requirements of many SSL test methods imposed by various national and regional metrology standards. The Annex Test Method encompasses all the requirements contained in the SSL test methods already available in the USA, Japan, China, and also including the draft of the SSL test method being developed jointly by International Commission on Illumination (CIE) and Comité Européen de Normalisation (CEN).

The terms used in this section follow definitions in CIE S017 [CIE-11], IEC 62504 [IEC-14], IEC 60050[4] and LM-79:08 [IES-08]. The following summarizes the most important features of the testing protocol.

Ambient Conditions: The ambient temperature during the measurement of the product shall be maintained at (25±1) °C. The temperature sensor shall be placed at the same height and within 1 m of

[4] http://www.electropedia.org/

the LED lamp under test. Airflow around the tested lamp shall be maintained at less than 0,2 m/s such that normal convective airflow induced by device under test is not affected.

Position & Stabilization: The operating position of lamps shall be specified according to the normal use conditions of the product. Prior to taking measurements, the product under test shall be operated at the rated condition and allowed to stabilize so that the changes in electrical power and total luminous flux are less than 0,5% over a 30-minute window, based on one-minute monitoring. If necessary, longer stabilization time can be considered and in the case that the lamp is not stabilized the measures are taken 2 h after the switch-on time.

Electrical measurement conditions: The lamps under test have been operated at the rated voltage (230 V AC) and frequency (50 Hz). The tolerance of the test voltage for AC-input is ±0,2% of the rated value and the tolerance of frequency is ±0,2%. AC power supplies used for this testing shall have a sinusoidal voltage wave shape at the prescribed frequency with the total harmonic distortion not exceeding 3% under a resistive load. If the product has dimming capability, measurements shall be performed at the maximum input power condition. The RMS voltage (V), current (A), power (W), and power factor, shall be measured at the time photometric measurements are taken. The AC power meters used for this testing shall have a sampling rate that is capable of resolving the current wave for the tested product: 61000-3-2 [IEC-14a] states that the electrical characteristics of lighting products should be analysed in a frequency range covering the fundamental (50 Hz) and up the 40th order (2 kHz). EN/IEC 61000-4-7 [IEC-02] indicates that power measurement equipment should be able to analyse components up to 9 kHz.

Photo-colorimetric measurement conditions: For the measurement of total luminous flux, CCT, chromaticity tolerance (Δu'v') and CRI a sphere-spectroradiometer shall be used at each testing laboratory. These devices shall be calibrated with a total spectral radiant flux standard traceable to a National Metrology Institute (NMI). The spectroradiometer used shall cover the wavelength range of at least 380 nm to 780 nm, and the bandwidth (full width half maximum) and scanning interval no greater than 5 nm. Wavelength scale uncertainty shall be within 0,3 nm. Colour quantities measured for tested products include correlated colour temperature (CCT), and general Colour Rendering Index (CRI).

Useful luminous flux definition: this quantity is used only for directional lamps other than filament lamps and it is defined by EU regulation No 1194/2012 as follows: directional lamps with a beam angle ≥ 90° and carrying a warning on their packaging in accordance with point 3.1.2(j) of the above sited EU regulation Annex: rated luminous flux in a 120° cone, other directional lamps: rated luminous flux in a 90° cone.

Luminous efficacy definition: The luminous efficacy, η, expressed in lumens par watt (lm/W) of the product under test is determined by the following relation

$$\eta = \frac{\Phi}{P}$$

where P and Φ are respectively the electrical input power and the total luminous flux, measured following the above described methodology.

Power Factor definition: The power factor (PF) and cosφ are defined as follows:

$$PF = \frac{P}{VI} \text{ and } cos\varphi = \frac{P}{V_0 I_0}$$

where P, I and V are respectively the RMS electrical input power, current and voltage; I_0 and V_0 are the voltage and current sinusoidal terms at 50 Hz.

Cross-laboratory calibration

Product conformity was tested in the three laboratories that have all the necessary, certified equipment for these types of measurements: Toulouse University – LAPLACE laboratory (France), Swedish Technical Research Institute (Sweden) and the Laboratory of City of Vienna (Austria). The three laboratories compared the performance of three test-lamps according to a set agreement. The three lamps used for this inter-laboratory round-robin test are shown in Table 2.

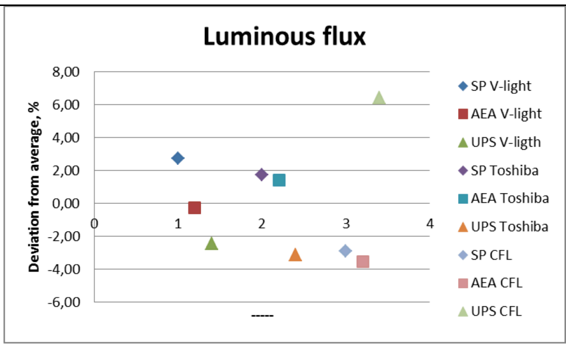
Table 2: Cross-laboratory calibration lamps

Manufacturer	Model	Nominal Correlated Colour Temperature [K]	Rated AC voltage [V]
V-light	LED bulb E27	2700	230
Toshiba	LED spot 25	<3000	230
Govena	CFL	<3000	230

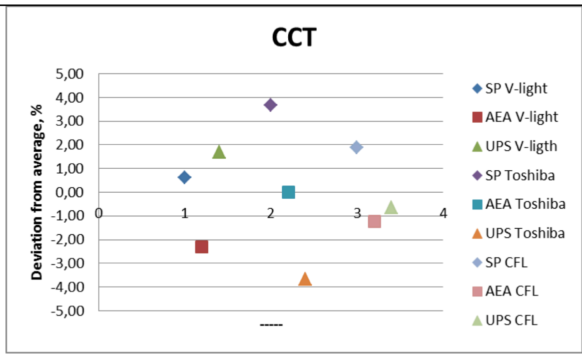
Each laboratory measured the luminous flux, correlated colour temperature and Colour Rendering Index for all three test-lamps. Figure 1 summarizes all three laboratories deviations for each lamp and each of the measured quantities. The maximal deviation of each of the above three quantities ("A") has been defined as follows:

$$\Delta A_{\max}(\%) = \pm \max\left\{100\left(1-\frac{\bar{A}_i}{\bar{A}}\right)\right\}$$

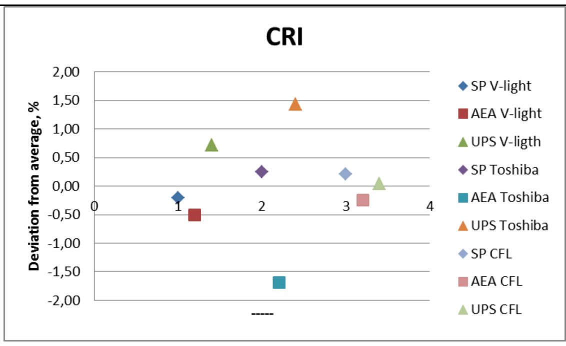
where $\bar{A}_i$ is the average given by the ith laboratory and $\bar{A}$ is the global average value.



(a)



(b)



(c)

Figure 1 : Comparison for (a) Total Luminous flux; (b) Correlated Colour Temperature; (c) Colour Rendering Index for the three artefacts.
Values are given in deviation from average in percent %. 0 = average value for all three laboratories.
Laboratories: Swedish Technical Research Institute (SP-V); Toulouse University – LAPLACE laboratory (UPS); Laboratory of City of Vienna (AEA)

The above figures show that all three laboratories obtained consistent results for all tested photometric quantities. The results from 3 laboratories were collected and analysed. These results shown that (1) values for Luminous flux in lumens deviated at maximum of ± 6,0 %; (2) values for Correlated Colour Temperature in kelvin deviated at maximum of ± 4,0 %; (3) values for Colour Rendering Index deviated at maximum of ± 1,5 %.

Results

Comprehensive testing of the high efficiency lamp products is now complete. More than 330 lamps of 85 different types were tested during the project. For each model a sample of three to five lamps were tested. This sample size can be considered as relatively small but for products like lamps manufactured at large batches by industrial machines it can be considered as representative. Increasing the sample size implies larger testing times and higher testing cost. Our results shown that for all lamps of the same brand the standard deviation for each studied quantity stayed at acceptable low level (<5%). Lamps types included:

- 49 types of LED omnidirectional and candle-type lamps (sockets E27, E14, B22d and B15d),
- 35 types of LED spots (sockets: E27, E14, GU10, GU5.3, GU5 and GU4) and 1 model of AR111 downlight.

Figures 2 and 3 show the measured total luminous flux versus the measured input power for omnidirectional LED lamps and LED spots. For spots the maximum luminous efficacy was found to be 94 lm/W and the minimum value was 30 lm/W. In the case of omnidirectional lamps these values were 104 lm/W and 47 lm/W respectively. We saw also that some omnidirectional LED lamps offered a luminous flux equivalent to a 75W GLS lamp (1,000 lm). Furthermore, the AR111 downlight produce a flux of more than 1,000 lumens.

Input power declarations by manufacturers were found to conform generally to measurements within a ±10% confidence interval: one model of LED omnidirectional lamp showed a 21% deviation for input power, but almost 33% of the LED spots were outside of this interval. The situation is different for total luminous flux values: 63% of the omnidirectional LED lamps and only 39% of LED spots were within a ±10% interval of manufacturer declared values[5]. For one LED spot model the deviation was 109%.

We also observed a change in the average efficacy of lamps between the two rounds of testing in 2013 and 2014. For omnidirectional LED lamps the average luminous efficacy increased by 8% for LED spots by 29% within this single year.

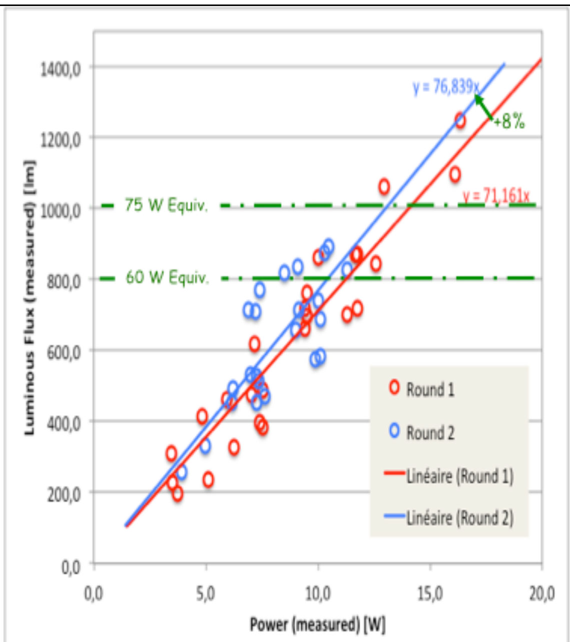


Figure 2: Measured luminous flux (lm) vs measured electrical power (W) for LED omnidirectional lamps (each point is the average of 3 to 5 measured lamps)

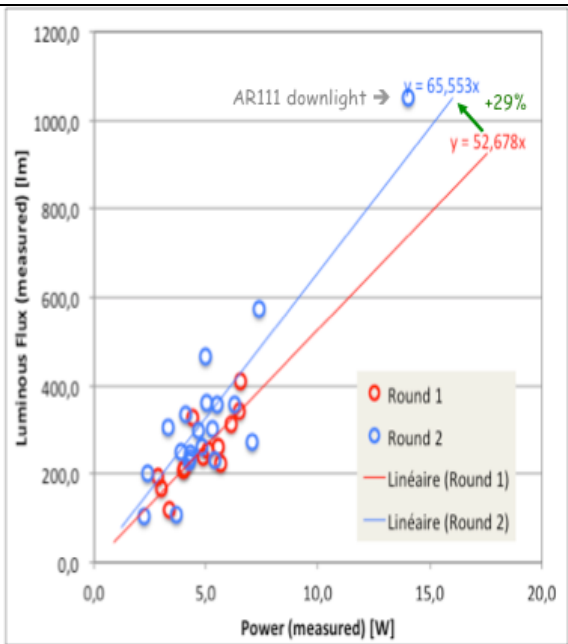


Figure 3: Measured luminous flux (lm) vs measured electrical power (W) for LED spots (each point is the average of 3 to 5 measured lamps)

Figure 4 and 5 show that for LED omnidirectional lamps 15% of the batch had an efficacy lower 60 lm/W and for LED spots 31% of the batch had efficacy lower than 50 lm/W (limit values fixed for PremiumLight quality).

[5] Following EU directive 2009/125/EC, deviation higher than ±10% between the declared and measured for input power and for luminous flux values has to be considered as not acceptable.

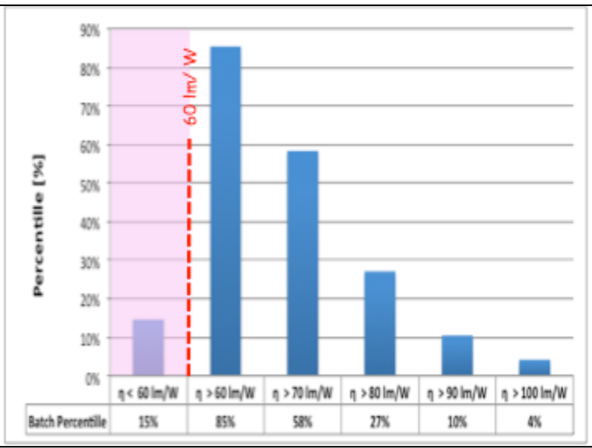


Figure 4: Luminous efficacy distribution among the examined omnidirectional LED lamp batch

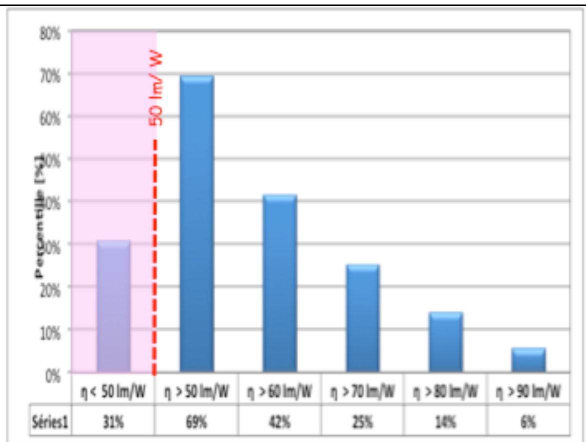


Figure 5: Luminous efficacy distribution among the examined LED spot batch

Figure 6 compares the EEI[6] declared values for omnidirectional LED lamps to our measurements. Significant deviations are detected but only 6 models are labelled incorrectly (four models are declared to be A class, but we found them to be A+ class, and two models were declared to be A+ and we found them to be A). The majority of studied lamps are A+ products (70,8% of the batch) and none B energy class has been found in the full batch. However 29,2% of the models are class A and don't fulfil PremiumLight quality requirements.

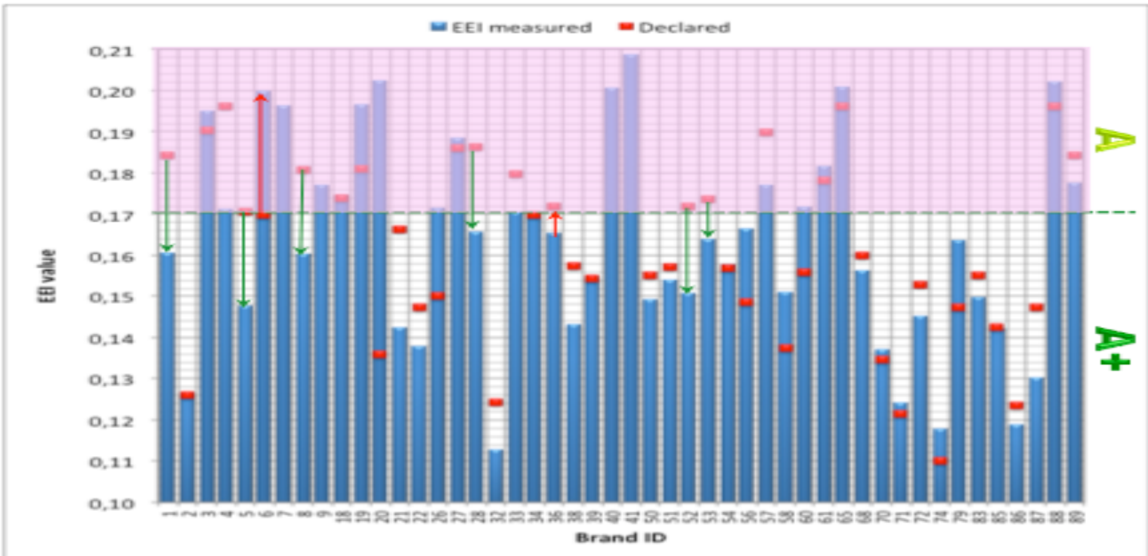


Figure 6: EEI and energy class measured (blue bars) and declared (red dots), products in red shaded part of the plot do not fulfill PremiumLight requirements

Concerning power factor, the large majority of the lamps and spots measured values higher than 0,5 as requested by the last EU-ecodesign directive and are acceptable for the European market. Figure 7 shows the results for omnidirectional lamps. However, as can be seen from figure 8 there are significant differences between power factor and cosφ, these two values are very often mixed in the manufacturer declarations. This difference is due to the fact for some products the electric current waveform may deviates significatively from sinus wave and in that case the Total Harmonic Distrortion of the current is very high. If the current form is purely sinoisoidal then power factor and cosφ should be strictly equal.

[6] For omnidirectional and spot lamps EEI values are defined following EU Directive 92/75/EC

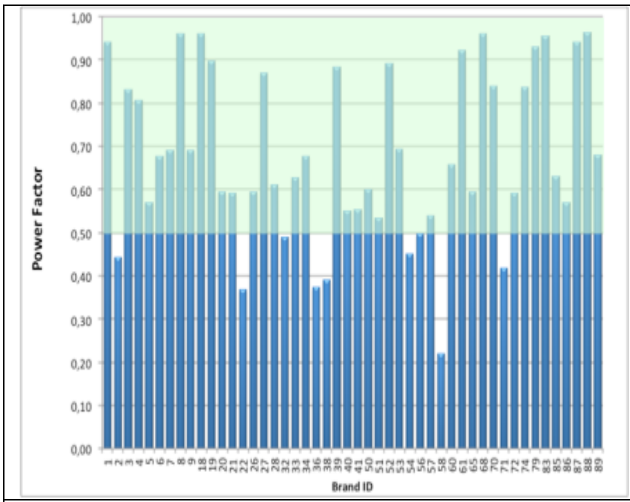


Figure 7: Measured Power Factor for omnidirectional LED lamps

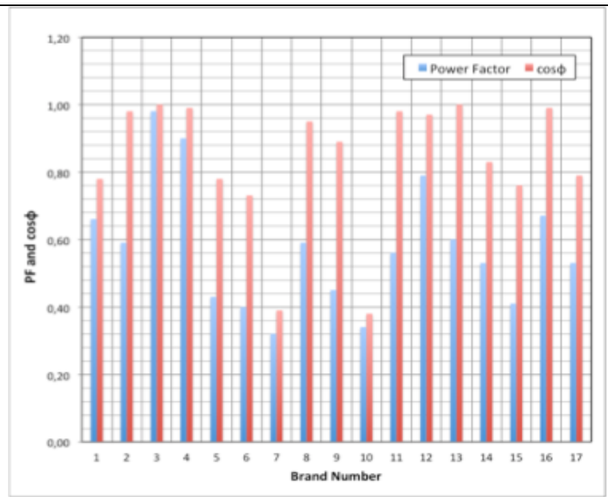


Figure 8: Power Factor (blue bars) and cosφ (red bars) values for some lamps of the batch

Concerning light colour characteristics, all tested lamp types, but one, were warm white (CCT<3,100 K). Only minor deviations between declared and measured values were observed. Colour temperature only varied within ±5% confidence interval.

Figures 9 and 10 show the results concerning colour-rendering index for omnidirectional LEDs and LED spots. The figures show that most tested lamps showed a measured CRI of around 80, therefore above the minimum level currently required by the eco-design regulation (CRI verification tolerance of less than 4 points as shown in figures 9 and 10). Thus the CRI of most of the LEDs tested is at a standard level and not particularly high. However, we found in the studied batch already lamp models available with a CRI around or above 90, therefore significantly better. Thus also LED-lamps for specific purposes where high colour rendering is needed are available today.

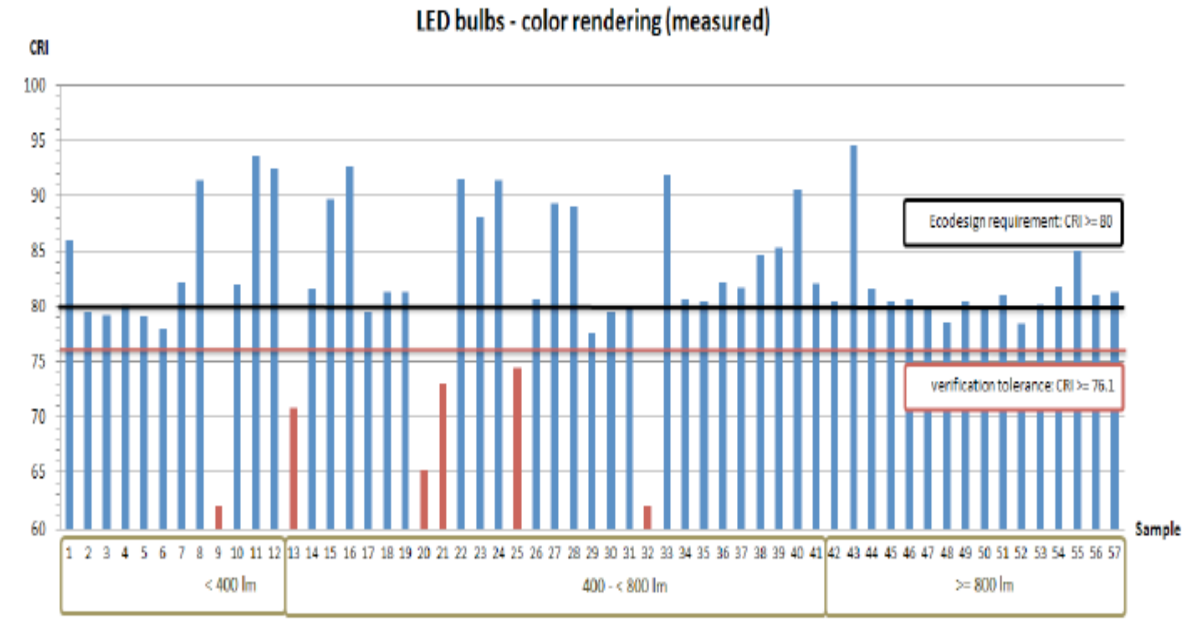


Figure 9: Measured CRI for LED omnidirectional lamps

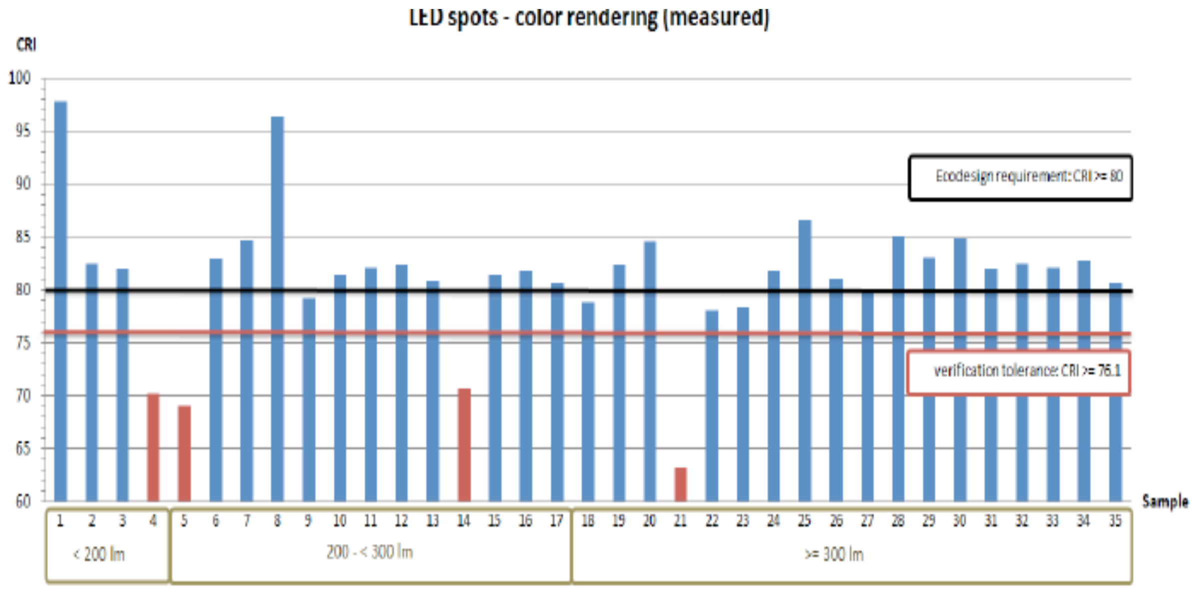


Figure 10: Measured CRI for LED spots

Finally, figure 11 shows the declaration errors for the colorimetric characteristics (CCT and CRI) for omnidirectional LED lamps. Deviations higher than ±5% are not acceptable. It is evident that compliance CRI requirements, with a maximum observed deviation 25,4%, is much more difficult for manufacturers than consistency with CCT declarations (maximum observed deviation 10,5%).

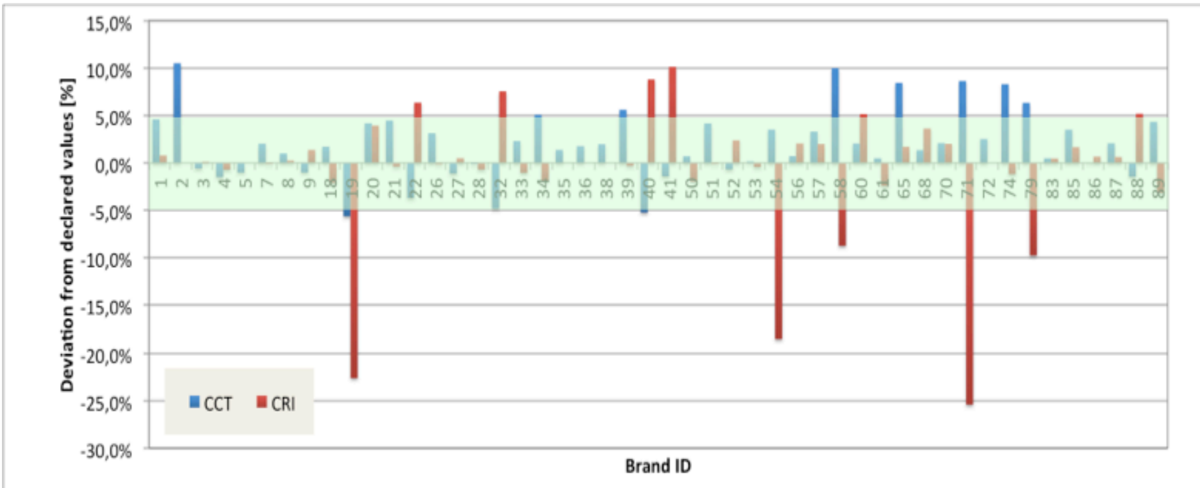


Figure 11: Measured deviations for colorimetric characteristics for omnidirectional LED lamps

Conclusions

Overall, PremiumLight's extensive lamp testing showed that very efficient, high-quality, LED lamps are available today with efficacy levels up to 104 lm/W (for an omni-directional LED bub), CRI up to 95 and up to 1040 lm output for an AR111. Many of LED bulbs were confirmed to be A+ class and to have Power Factors higher than 0,5. Our measurements showed that many tested products had a Colour Rendering Index of 90 and even higher. Thus the light quality offered by the lamps tested, at least in terms of colour rendering, is already approaching levels close to halogen lamps and the standard incandescent lamp.

Even if 2 years aren't enough to get a clear trend, our measurements shown that average lamp efficacy appears to be increasing: the average luminous efficacy for LED bulbs improved from 71 lm/W observed in round 1 to 77 lm/W in round 2. For LED directional lights efficacy improved from 53 lm/W to 66 lm/W or more than 29% in one year. This tendency is also confirmed by other independent measurements in the frame of national programs like US-Caliper.

The performance of the LED products tested conform, in large part to the manufacturers' declarations, but some singular cases of significant deviations from declared performance were found.

Although the majority of the tested lamps showed high quality and efficacy, our results also indicated that some brands do not provide the quality and efficacy claimed by manufacturers. Such products showed problems regarding efficacy, luminous flux, colour rendering and other quality aspects.

Overall, the results of the PremiumLight testing suggest that many efficient, high quality, LED products are available to European consumers today. However, some products did show significant deviations from manufacturer claims for lumen output, energy efficiency, or other factors. Consumers are advised to consult third-party independent test results to ensure satisfaction with LED lighting products.

Acknowledgments

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Evaluating the Combined Impact of Financial incentives, Tax Incentives, Information and Minimum Energy Performance Standards in Transforming a Residential Appliance Market

K. H. Tiedemann and I. M. Sulyma

BC Hydro and Research 4 Results

Abstract

BC Hydro has provided financial, technical and administrative support for the development and implementation of an Energy Star Appliance program in British Columbia, Canada. This program has increased energy efficiency and reduced energy consumption of new residential appliances. From 2008 to 2014, the Appliances Rebate Program provided financial incentives on selected Energy Star labelled appliances, with the financial incentives supported by consumer information, sales tax incentives, and legislated Minimum Efficiency Performance Standards. The purpose of this study was to analyze the impact of these public policy instruments. Key results were as follows. First, the program has successfully addressed market barriers through information and promotions, sales tax exemption, financial incentives and legislative support for more stringent provincial Minimum Energy Performance Standards (MEPS). Second, the Energy Star refrigerator share increased from 57% in F2009 to 78% in F2012, and the Energy Star share clothes washer increased from 70% in F2009 to 79% in F2012. Third, un-aided customer awareness of Energy Star increased substantially over the period surveyed, from 46% in 2007:Q4 to 68% in 2010:Q2. Fourth, the price wedge between Energy Star and non-Energy Star appliances may have been substantial. Fifth, for the period F2008 to F2010, the program resulted in the purchase of an additional 26,778 Energy Star refrigerators and an additional 32,452 Energy Star clothes washers, with the additional Energy Star refrigerators saving 1.6 GWh of electricity per year and the additional Energy Star clothes washers saving 6.1 GWh of electricity per year. In summary, the use of multiple policy instruments has enabled BC Hydro and the Government of British Columbia to increase residential appliance efficiency, reduce residential energy consumption and transform the residential appliance market.

Introduction

Many observers have concluded that anthropogenic greenhouse gas emissions, including carbon dioxide, are the major cause of medium-term climate change. Since about two-thirds of greenhouse gas emissions are due to activities in the energy sector, reducing energy sector greenhouse emissions is viewed by many as critical in slowing the rate of increase in average global temperature. Policies aimed at reducing energy sector greenhouse gas emissions include reducing emissions from existing power generation facilities, developing new power generation sources with lower emissions, increasing energy prices to reduce energy consumption, and increasing end use energy efficiency.

Utilities, utility regulators, federal governments, state and provincial governments, and local and municipal governments in Canada and the United States have supported the voluntary Energy Star labelling program as one method of promoting the purchase and installation of energy efficient appliances and equipment and increasing end use energy efficiency. This support has included the development of appropriate standards and test procedures, advertising and other promotional activity, and financial incentives to reduce the initial cost of energy efficient appliances and equipment. Federal, state and provincial governments have also used Minimum Energy Performance Standards to ensure that appliances and equipment meet a minimum standard of energy efficiency.

Studies of the development, scope and impacts of Energy Star and related economic studies of appliance and equipment markets are listed in the References section. Some selected findings of this literature include the following:

- Energy Efficiency Potential. High energy prices should lead customers to seek energy efficiency improvements, but some research has found unexploited opportunities for cost-effective energy investments as discussed by Teitenberg (2009). Nadel et al. (2004) examined eleven studies and determined that the United States had substantial cost-effective energy efficiency potential, while Gellings et al. (2006) identified significant energy efficiency potential at the end use level.

- Market Failures and Barriers. The existence of unexploited cost-effective energy savings opportunities has led policy analysts to attempt to identify market failures and barriers which limit cost-effective investment in energy efficiency. These failures and barriers include negative environmental externalities [Teitenberg (2009)], missing, hidden or hard to obtain information on costs and benefits of energy efficiency investment [DeCanio (1998)], bounded rationality where consumers engage in satisficing behaviour [Dyner and Franco (2004)], split incentives where the agent making the investment does not capture the benefits of the investment [Sutherland (1991)], capital constraints [Taylor et al. (2008)], and status quo bias or non-optimizing behaviour [Kahneman et al. (1991)].

- Policy Responses. Governments, utility regulators and non-governmental organizations in North America have used a number of policy instruments in order to reduce the impact of these market failures and barriers. These include internalizing externalities through a carbon tax or a cap and trade system [Goulder and Parry (2008)], product certification such as Energy Star or LEED [Sanchez et al (2008)], minimum energy performance standards [Sanstad and Howarth (1994)], tradable white certificates [Langniss and Praetorius ((2006)],and financial incentives or subsidies [Nadel and Kushler (2000)].

- Policy Impacts. Measuring the impact of these policy responses has been a controversial area of research. One reason for this is that standard program evaluation methods including experiments, quasi-experiments or econometric modelling have not been widely applied in the energy efficiency field with estimates of policy impact depending too often on stake holder self-report surveys which have relatively low internal validity and accuracy. Some key studies include Joskow and Marron (1993) who found that the cost of conserved energy at ten utilities was significantly higher than suggested by cost of conservation supply curves, Howarth (2000) who examined the role of the office equipment component of Energy Star in overcoming multiple barriers to energy efficiency, and Sanchez et al. (2008) who comprehensively estimated the impact of the wide set of Energy Star standards based on bottom up engineering algorithms.

Despite the substantial size of this literature, few published studies have rigorously estimated the impact of financial incentives on the purchase and installation of Energy Star qualifying household appliances, or the consequent impact on energy consumption, using appropriate statistical modelling procedures. The purpose of this study is to help fill this gap by using appropriate engineering field measurement combined with appropriate time-series modelling to estimate the impact of a utility Energy Star residential appliance program.

Approach

For this study, there were five main activities: (1) conduct a program review; (2) undertake a supply-side assessment; (3) undertake a demand-side assessment; (4) review price trends for Energy Star-qualifying and non-Energy Star-qualifying appliances; and (5) estimate energy and peak savings. The study approach used multiple lines of evidence, since no single line of evidence provided information on all of the evaluation issues. It should be noted that this study estimates the combined effect of all four policy instruments and not the effect of each instrument individually.

1. **Program Review.** To conduct the program review and develop the program logic model, we reviewed program documents, interviewed BC Hydro program staff, and conducted a literature review focussing on recent studies and reports of residential appliances.

2. **Supply-Side Assessment.** To undertake the supply-side assessment, we tabulated and examined relevant results of annual in-store surveys of appliance stock behaviour in representative samples of retail sales establishments. The surveys have about 40 participants per year.

3. **Demand-Side Assessment.** To undertake the demand-side assessment, we tabulated and examined relevant results of the quarterly Energy Star Tracker surveys, which track general residential customers' views and behaviours. The surveys have about 700 participants per quarter.

4. **Price Trends.** To review price trends for Energy Star and non-Energy Star appliances, we tabulated and examined relevant results from the annual in-store surveys.

5. **Energy and Demand Savings.** To estimate energy and peak demand savings, we used the following basic algorithms:

   (1) ΔkWh = Incremental number of units*unit energy savings,

   (2) ΔkW = Incremental number of units*unit peak demand savings.

The incremental number of units was based on an econometric demand model, and the unit energy savings were based on information on models available for sale from the in-store surveys.

Results

Program Review

By 2006, more than 230,000 major appliances were shipped to British Columbia each year for installation in new dwellings and as replacements for existing appliances. Following the implementation of a pilot program, subsequent engineering and economics analysis indicated that there were significant opportunities to reduce energy consumption in a cost-effective manner by increasing the penetration of Energy Star qualifying appliances. Energy Star is a voluntary standards and labelling program initially sponsored by the US Department of Energy which now has Natural Resources Canada, the European Union and others as partners. To be Energy Star labelled, manufactures must certify that a product meets the relevant energy efficiency guidelines. Typically, only the top 25% of products qualify for Energy Star status, and the specifications are periodically reviewed and revised as technology advances and products become more energy efficient.

By 2007, the BC Ministry of Energy, Mines and Petroleum Resources had developed a strategy aimed at transforming the residential appliance market in British Columbia. This strategy had four main steps as follows. Step 1. Seek approval for and launch the Energy Star Appliances rebate program. Step 2. Provincial government makes energy efficient appliances a priority for regulation. Step 3. Obtain provincial sales tax (PST) exemption for Energy Star appliances. Step 4. Market penetration of Energy Star appliances increases significantly and energy efficiency legislation for refrigerators and clothes washers is passed.

Based on a review of provincial government reports, program documents, and interviews with program staff and stakeholders it was determined that the Energy Star Appliances program had four main components as follows:

- Information and Promotions. Consumer knowledge of and interest in Energy Star qualifying appliances was addressed through advertising, point of sale material and improved labelling of products. Salesperson awareness and attention was addressed through training offered to sales staff so that they could sell the benefits of Energy Star qualifying appliances to potential customers.

- Sales Tax Exemption. Exemption from the 7% Provincial Sales Tax (PST) from April 1, 2008 through March 31, 2010 for eligible Energy Star qualifying refrigerators, freezers, and clothes washers.

- Financial Incentives. A $50 customer incentive for Energy Star qualifying refrigerators and clothes washers and $25 customer incentive for Energy Star qualifying freezers was offered from April 1, 2008 through March 31, 2010 in order to reduce the perceived cost difference between Energy Star and non-Energy star qualifying appliances. As of June 1, 2010, BC Hydro offered customer incentives on selected appliances which were more energy efficient than Energy Star.

- Legislative Support. Amendments to the Energy Efficiency Act were brought into force to harmonize BC regulations with proposed US Department of Energy regulations for refrigerators (September 15, 2014), freezers (September 15, 2014) and clothes washers (March 7, 2015).

Table 1 presents a program logic model which summarizes the inputs-outputs-purpose-goal linkages for each of the four activities. Since each of the linkages for each of the activities is plausible, the overall logic of the program is sound.

Table 1. Program Logic Model

	Information and Promotions	**Sales Tax Exemptions**	**Financial Incentives**	**Legislative Support**
Inputs	Develop information and promotional materials and distribute these materials to wholesalers and to retailers	PST (7%) exemption for Energy Star clothes washers, freezers and refrigerators through March 31, 2010	$50 incentive for Energy Star refrigerators and clothes washers and $25 incentive for freezers through March 31, 2010	Technical and financial support for energy efficient appliance standards and test procedures development
Outputs	Customer product awareness increased	First cost of Energy Star appliances reduced	First cost of Energy Star appliances reduced	Minimum energy performance standards in place
Purpose	Increased customer intent to purchase Energy Star qualifying appliances	Increased customer purchase of Energy Star qualifying appliances	Increased customer purchase of Energy Star qualifying appliances	Prevent energy efficiency backsliding in the residential appliance market
Goal	Significantly increase market share of Energy Star appliances and acquire annual energy savings of 4.9 GWh by March 2010			

Supply-side Assessment

Refrigerators typically have one of three configurations: the freezer compartment is mounted below the refrigerator compartment (bottom); the freezer compartment is mounted on the top of the refrigerator compartment (top); or the freezer and refrigerator compartments are side by side (side by side). Table 2 shows the refrigerator stock share by configuration. The share of top mount refrigerators decreased from 27% in F2009 to 24% in F2012. The share of bottom mount refrigerators increased from 53% in F2009 to 66% in F2012. The share of side by side refrigerators decreased from 20% in F2009 to 10% in F2012.

Table 2. Refrigerator Stock Share by Configuration (%)

	F2009	**F2010**	**F2011**	**F2012**
Top	27	26	26	24
Bottom	53	56	61	66
Side by side	20	19	13	10
Total	100	100	100	100

Table 3 shows the share of refrigerators qualifying for Energy Star by configuration. The Energy Star share of top mount refrigerators increased from 43% in F2009 to 62% in F2012. The Energy Star share of bottom mount refrigerators increased from 64% in F2009 to 92% in F2012. The Energy Star share of side by side refrigerators increased from 70% in F2009 to 92% in F2012. The Energy Star share of all refrigerators increased from 57% in F2009 to 85% in F2012.

Table 3. Refrigerator Energy Star Qualifying by Configuration (%)

	F2009	F2010	F2011	F2012
Top	43	64	53	62
Bottom	64	83	88	92
Side by side	70	83	88	92
Total	57	78	79	85

Clothes washers typically have one of two configurations: front-load and top-load. Table 4 shows the clothes washer stock share by configuration. The share of front-load clothes washers decreased from 70% in F2009 to 69% in F2012. The share of top-load clothes washers increased from 30% in F2009 to 31% in F2012.

Table 4. Clothes Washer Stock Share by Configuration (%)

	F2009	F2010	F2011	F2012
Front-load	70	73	77	69
Top-load	30	27	23	31
Total	100	100	100	100

Table 5 shows the share of clothes washers qualifying for Energy Star by configuration. The Energy Star share of front-load clothes washers increased from 88% in F2009 to 96% in F2012. The Energy Star share of top-load clothes washers increased from 22% in F2009 to 62% in F2012. The Energy Star share of all clothes washers increased from 70% in F2009 to 85% in F2012.

Table 5. Clothes Washer Energy Star Qualifying by Configuration (%)

	F2009	F2010	F2011	F2012
Front-load	88	91	96	96
Top-load	22	64	64	62
Total	70	79	88	85

Demand-side Assessment

To understand customer awareness of Energy Star, survey respondents were first asked “have you seen or heard of the Energy Star label,” and those who responded positively were viewed as having unaided awareness of Energy Star. Those who responded negatively were then asked ”please look at the Energy Star label: have you seen or heard of this label”, and those who now responded positively were viewed as having aided awareness of Energy Star, with total awareness then defined as the sum of aided and unaided awareness. Table 6 shows the results of the Energy Star awareness questions. Unaided awareness of Energy Star increased from 46% in F2008 to 68% in F2011, while total awareness of Energy Star increased from 72% in F2008 to 85% in F2011.

Table 6. Overall Energy Star Awareness (%)

	F2008	F2009	F2010	F2011
Un-aided	46	50	62	68
Aided	26	26	19	17
Total	72	76	81	85

Survey respondents who purchased various products in the twelve months before survey administration were asked a series of questions about the products they purchased and about the labels on these purchased products. Table 7 shows the results of the Energy Star label recall questions. For those survey respondents who purchased a refrigerator, Energy Star label recall increased from 51% in F2008 to 62% in f2011, while for those survey respondents who purchased a clothes washer, Energy Star recall increased from 58% in F2008 to 65% in F2011.

Table 7. Energy Star Recall by Appliance Purchasers (%)

	F2008	F2009	F2010	F2011
Refrigerators	51	57	55	62
Clothes washers	58	53	61	65

Those survey respondents who recalled seeing the Energy Star label were then asked about the importance of the Energy Star label on their purchased decisions. Table 8 shows the relevant top box scores, that is, the sum of those for whom the Energy Star label was very influential on their purchase decisions plus those for whom the Energy Star label was somewhat influential in their purchase decisions. The top box score for those purchasing a refrigerator fell slightly from 86% in F2008 to 85% in F2011, while the top box score for those purchasing a clothes washer increased slightly from 90% in F2008 to 95% in F2011.

Table 8. Energy Star Gross Purchase Influence (% very plus somewhat influential)

	F2008	F2009	F2010	F2011
Refrigerators	86	81	88	85
Clothes washers	90	95	86	95

We defined Energy Star net purchase influence as the product of the share of respondents who recalled seeing an Energy Star label on their appliance (from Table 7) times the share of respondents who stated that the label was very or somewhat influential in their purchase decisions (from Table 8). This can be interpreted as one way to measure the net to gross ratio. Table 9 shows the results of these calculations. Energy Star net purchase influence for refrigerators increased from 44% in F2008 to 53% in F2011, while Energy Star net purchase influence for clothes washers increased from 52% in F2008 to 62% in F2011.

Table 9. Energy Star Net Purchase Influence (% very plus somewhat influential)

	F2008	F2009	F2010	F2011
Refrigerators	44	46	48	53
Clothes washers	52	50	52	62

Price Trends

Trends in refrigerator prices were based on detailed information collected during the in-store surveys. Table 10 shows the trends in refrigerator prices by configuration. Average price for top mount refrigerators decreased from $766 per unit in F2008 to $715 per unit F2012. Average price for bottom mount refrigerators increased from $1961 per unit in F2008 to $1926 per unit F2012. Average price for side by side refrigerators decreased from $1895 per unit in F2008 to $1714 per unit F2012. Average price for all refrigerators increased from $1501 per unit in F2008 to $1613 per unit F2012.

Table 10. Refrigerator Prices by Configuration (dollars per unit)

	F2009	F2010	F2011	F2012
Top	766	747	689	715
Bottom	1961	1847	1851	1926
Side by side	1895	2005	1870	1714
Total	1501	1590	1528	1613

Table 11 shows the trends in refrigerator prices by Energy Star qualification. Average price for Energy Star qualifying refrigerators increased from $1586 per unit in F2008 to $1706 per unit F2012. Average price for non-Energy Star qualifying refrigerators decreased from $1364 per unit in F2008 to $1047 per unit F2012.

Table 11. Refrigerator Prices by Energy Star Qualification (dollars per unit)

		F2009	F2010	F2011	F2012
Top	Energy Star	839	806	779	795
	Non-ES	713	645	586	584
Bottom	Energy Star	1925	1858	1812	1922
	Non-ES	1776	1495	2267	1983
Side by side	Energy Star	1783	1918	1470	1730
	Non-ES	2160	2159	1586	1501
Total	Energy Star	1586	1646	1632	1706
	Non-ES	1364	1219	1101	1047

Trends in clothes washer prices were also based on detailed information collected during the in-store surveys. Table 12 shows the trends in clothes washer prices by configuration. Average price for front-load clothes washers decreased from $1275 per unit in F2008 to $1189 per unit F2012. Average price for top-load clothes washers increased from $637 per unit in F2008 to $838 per unit F2012. Average price for all clothes washers decreased from $1105 per unit in F2008 to $1080 per unit F2012.

Table 12. Clothes Washer Prices by Configuration (dollars per unit)

	F2009	F2010	F2011	F2012
Front-load	1275	1331	1167	1189
Top-load	637	701	748	838
Total	1105	1149	1061	1080

Table 13 shows the trends in clothes washer prices by Energy Star qualification. Average price for Energy Star qualifying clothes washers decreased from $1266 per unit in F2008 to $1124 per unit F2012. Average price for non-Energy Star qualifying clothes washers increased from $755 per unit in F2008 to $927 per unit F2012.

Table 13. Clothes Washer Prices by Energy Star Qualification (dollars per unit)

		F2009	F2010	F2011	F2012
Front-load	Energy Star	1288	1347	1177	1196
	Non-ES	829	892	962	1056
Top-load	Energy Star	1213	1174	856	965
	Non-ES	583	547	542	640
Total	Energy Star	1266	1300	1103	1124
	Non-ES	755	799	866	927

Energy and Demand Savings

Energy and peak savings were estimated in several steps. First, unit energy savings were calculated for each appliance, using the information on the Energy Star labels. Second, the program impact on shipments of Energy Star appliances was estimated using an econometric model. Third, results of the regression model were used to estimate the program impacts on appliance shipments. Fourth, engineering algorithms were used to estimate energy and peak impacts.

Step 1. The following algorithm was used to estimate energy savings per unit for appliance j:

$$(3)\ Unitsav_j = (Non\text{-}ESsavekWh_j - ESsavekWht_j) * (Volume_j) * (1 - Crosseffects_j).$$

The results are shown in Table 3.10. Unit savings for clothes washers were estimated to be 188.0 kWh per year. Unit savings for refrigerators were estimated to be 55.9 kWh per year.

Table 14. Unit Energy Savings

	ES (kWh per cubic ft)	Non-ES (kWh per cubic ft)	Volume (cubic ft)	Cross effects (%)	Savings (kWh per unit)
Clothes washers	48	95	3.9	-	188.0
Refrigerators	23	26	20.3	8.2	55.9

Step 2. The following monthly econometric model for the period January 2003 to March 2010 was used to estimate the impact of the program on monthly appliance shipments:

$$(4)\ Ship_m = \alpha + \beta Perm_m + \gamma Wage_m + \delta PSARP_m + \theta\ Q2_m + \lambda Q3_m + \eta Q4_m + \varepsilon_m$$

where variables (and their sources) are as follows: Ship is shipments of ES qualifying refrigerators and clothes washers (from CAMA). Perm is residential building permits (from BCStats); wage is wage rate (from BCStats); PSARP is dummy variable for presence of program (program); Q2, Q3 and Q4 are quarterly dummy variables; ε is an error term.

Results using ordinary least squares regression are shown in Table 15. The regression results are good with an adjusted R-squared of 0.66, and all of the coefficients are significant at the 10% level. The key point is that realization on the program variable is 2,355 units per month compared to program incentives of 4,874 for clothes washers and refrigerators for a realization rate of 48.3%.

Table 15. Regression Results for Refrigerators and Clothes Washers

Variable	Coefficient	Standard error
Constant	-18686*	9584
PSARP	2355***	824
Wage	28.2**	12.9
Building permits	0.0049***	0.0012
Q2	1045**	501
Q3	1582***	494
Q4	1374***	501
Adjusted R-squared	0.66	

One, two and three asterisks mean that the coefficient is statistically significant at the 10%, 5% or 1% level respectively.

Step 3. The following algorithm was used to estimate net units shipped for appliance j:

$$(5)\ Net\ unit_j = Rebates\ per\ month_j * Net\ to\ gross\ ratio.$$

Results are shown in Table 16. As explained above, a common net-to-gross ratio of 0.483 is applied to the average number of rebates per month. The number of units attributable to program activities per month is 1,249 clothes washers and 1,106 refrigerators.

Table 16. Net Units per Month

	Rebates per month	Net to gross ratio	Net units per month
Clothes washers	2584	0.483	1249
Refrigerators	2290	0.483	1106

Step 4. The following algorithm was used to estimate energy savings for appliance j:

(6) Energy savings$_j$ = Unit savings$_j$ *Change in net number of units$_j$.

Results are shown in Table 17. For clothes washers, annual energy savings are 6.1 GWh and annual peak savings are 1.9 MW. For refrigerators, annual energy savings are 1.6 GWh and annual peak savings are 0.5 MW.

Table 17. Energy and Peak Savings

	Savings (kWh per unit)	Change in net number of units	Energy (GWh per year)	Peak (MW per year?)
Clothes washers	188.0	32474	6.11	1.91
Refrigerators	55.9	28756	1.61	0.51
Total			7.72	2.45

Conclusions

BC Hydro has provided financial, technical and administrative support for the development and implementation of an Energy Star Appliance program in British Columbia, Canada. From 2008 to 2014, the Appliances Rebate Program provided financial incentives on selected Energy Star labelled appliances, with the financial incentives supported by consumer information, sales tax incentives, and legislated Minimum Efficiency Performance Standards.

This study has five main findings as follows:

- Program Review. At the time of program launch, a market analysis included in the business case indicated that there were several barriers to market transformation including low awareness of Energy Star appliances among consumers, low availability of Energy Star product in stores, and high prices for Energy Star products. BC Hydro has employed a phased strategy to transform the household appliance market and acquire energy and peak savings. The program has successfully addressed these barriers through four main activities: information and promotions, sales tax exemption, financial incentives and legislative support for more stringent Minimum Energy Performance Standards (MEPS).

- Supply Side Assessment. The product shares for refrigerators were as follows: bottom-mount - 56%, top-mount - 26%, side by side - 19%. The Energy Star refrigerator share increased from 57% in F2009 to 78% in F2012. The product shares for clothes washers were as follows: front load - 73%; top load - 27%. The Energy Star share clothes washer increased from 70% in 2009 to 79% in 2010.

- Demand Side Assessment. To determine unaided awareness of Energy Star, respondents were asked “Have you seen or heard of the Energy Star label?” Those who indicated yes were viewed as having unaided awareness of the Energy Star label. Those who responded no to this first question were asked “Please look at the Energy Star label: have you seen or heard of this label?” Those who responded yes were added to the unaided aware to determine total awareness. Unaided awareness has increased substantially over the period surveyed, from 46% in 2007:Q4 to 68% in 2010:Q2. Total awareness has also increased, rising from 72% in 2007:Q4 to 85% in 2010:Q4.

- Price Trends. Appliance price comparisons are complicated because prices are driven by a number of factors including volume, features, materials used as well as whether or not they are Energy Star compliant. The prices for major appliances by Energy Star status were compared using the in-store surveys, and these surveys suggest that the wedge between Energy Star and non-Energy Star appliances may have been substantial.

- Energy and Peak Demand. For the periods F2008-F2010, the program resulted in the purchase of an additional 26,778 Energy Star refrigerators and an additional 32,452 Energy Star clothes washers. The additional Energy Star refrigerators saved 1.6 GWh of electricity per year and the additional Energy Star clothes washers saved 6.1 GWh of electricity per year. The additional Energy Star refrigerators reduced peak demand by 0.51 MW and the additional Energy Star clothes washers reduced peak demand by 1.91 MW.

In conclusion, the use of multiple policy instruments has enabled BC Hydro and the Government of British Columbia to increase residential appliance efficiency, reduce residential energy consumption and transform the residential appliance market.

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Analysis of Consumer Preferences for Residential Lighting through Consumer Panel Data

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Abstract

We first investigate trends of residential general service light bulb sales in the U.S. derived from a consumer panel dataset spanning from 2004 to 2009 and including about 100,000 nationally representative households. Total light bulb sales are observed to decrease almost monotonically over the period, while CFL sales gradually increased until 2007 and then decreased in following years. Within the period, new CFL products represented by unique universal product codes (UPC) are constantly introduced to the market, while the number of distinct UPCs of incandescent lamps stays constant. Even with the continuing variety of incandescent bulbs, constantly shrinking sales of incandescent lamps show that the market is transforming. Sales are heavily concentrated to several key retailers, which implies that efforts taken by these retailers could influence nationwide adoption of efficient lighting.

We then analyze consumer preferences for light bulbs by estimating choice models, from which we estimate willingness-to-pay (WTP) for attributes (watt and type) and implicit discount rates (IDR) for lighting purchases. We show that the campaign for efficient bulbs by a large retailer in 2007 is potentially related to the peak in CFL purchases. IDRs for four representative states range between around 230% and 330%, a similar range we estimated from stated preference data in our earlier study, which indicates that barriers to energy efficient lighting continue throughout the period we observe.

Introduction

In this study, we characterize the light bulb market and highlight key regional trends from 2004 to 2009. This period witnessed two important events for energy-efficient lighting. First, the Energy Independence and Security Act (EISA) was enacted in 2007 setting standards on the luminous efficacy of light bulbs. The EISA of 2007 defines that general service lamps have medium screw bases and light outputs of between 310 and 2600 lumens (1). These light bulbs are the focus of our analysis. The EISA standards were established as follows. General service lamps should satisfy the requirement shown in Table 1 if they are produced after the effective dates in the last column. For example, EISA contemplates that starting from January 1, 2012, all light bulbs manufactured with a rated lumen range between 1490 and 2600 should not exceed 72W and have to have rated lifetimes longer than 1000 hours. Most CFLs and LEDs that are currently being sold satisfy the requirements.

Table 1. Requirements of EISA 2007 for general service lamps [a]

Rated Lumen Ranges	Typical Current Lamp Wattage	Maximum Rate Wattage	Minimum Rated Lifetime	Effective Date
1490-2600	100	72	1,000 hrs	1/1/2012
1050-1489	75	53	1,000 hrs	1/1/2013
750-1049	60	43	1,000 hrs	1/1/2014
310-749	40	29	1,000 hrs	1/1/2014

[a] Source: (1)

Second, also in 2007, a key retailer Wal-Mart ran a nationwide campaign aiming to sell 100 million compact fluorescent lamps (CFL) by the end of 2007. Wal-Mart announced the plan at the end of November 2006 (2) and achieved the goal three months early at the end of September 2007 (3). Within that year, they sold 162 million CFLs (4). To realize the goal, Wal-Mart pursued several strategies, such as installing interactive displays in select stores starting from Jan 2007, increased shelf space for CFLs, released educational materials (e.g. online savings calculator, saving tips through Wal-Mart TV and radio, staff education through internal newsletter) (2), and also launched store-branded CFLs at lower prices than other brand products (5). It is not known whether they stopped all the promotion efforts after they achieved the goal, but they at least did not actively promote CFLs afterward (4).

In our earlier study (6), we conducted a choice-based conjoint field experiment with 183 participants, which contains a series of hypothetical light bulb choices. We estimated discrete choice models from the data. Greater willingness to pay for lower energy consumption and longer life was observed in conditions where estimated operating cost information was provided. Providing estimated annual cost information to consumers reduced their implicit discount rate by a factor of five, lowering barriers to adoption of energy efficient alternatives with higher up-front costs. However, even with cost information provided, consumers continued to adopt implicit discount rates of around 100%, which is larger than that observed for other energy technologies. This study will take the results from this earlier work and compare them with the findings from the revealed preference data in the consumer panel dataset.

In this work, we assess the trends in lighting sales for different lighting technologies across the country and by store type based on an extensive consumer panel dataset spanning from 2004 to 2009. Then, building on these observations, we attempt to investigate consumer preferences by estimating choice models, from which we assess which factors or events influences adoption of an efficient lighting technology. We also estimate willingness-to-pay (WTP) for light bulb attributes. After that, we estimate the implicit discount rates (IDR) that consumers use when making lighting choices. Finally, we compare the WTP and IDR estimates from using this real sales data (i.e., revealed WTP and IDRs) with the ones computed based on the experimental study in Min *et al.* (6).

Methods and data

Data description

We use a unique dataset acquired from a marketing firm, A.C. Nielsen, via the James M. Kilts Center for Marketing, at the University of Chicago Booth School of Business (7). The dataset contains six years of purchase data of household products with Universal Product Codes (UPC) from a nationally and regionally representative panel dataset that includes about 100,000 households, which have scanned their purchases from 2004 to 2009. We use the weighting factors provided in the dataset to estimate light bulb sales at the country or region level.

We selected purchases corresponding to general service light bulbs. Among those bulbs satisfying these criteria only the A-shape bulbs are considered in order to observe preferences for bulbs with similar use purpose. Brands that have less than 1% of total sales share were excluded. Also, bulb purchases that are not from the six major channels are removed. The six major channels of light bulbs purchases are discount stores, drug stores, hardware stores, groceries, warehouse clubs, and dollar stores, accounting for more than 96% of light bulb sales in any year. Only CFLs and incandescent bulb purchases are analyzed. Light-emitting diode (LED) bulb purchases are not considered because all purchase observations which can be categorized as LEDs are night lights or other non-general service lamps (e.g. too dim or different base types). This data selection process leads to a final set of 2,490 bulb products (differentiated by unique UPCs). From 2004 to 2009, about 75,000 distinct households purchased about 352,000 general service light bulb items. The final dataset contains four alternative-specific attributes of light bulbs: price, wattage, type, and package size. The price, type and package values are originally reported through dedicated fields in the Nielsen data, while wattage values had to be constructed based on the product description field provided by Nielsen.

Modeling method

With these data selected for general service light bulb purchases, we use a similar choice modeling method to the one used in the analysis in Min *et al.* (6). We model choices by a random utility model. The utility U_{ij} that consumer *i* draws from product alternative *j* is modeled as:

$$U_{ij} = V_{ij} + \epsilon_{ij} = \sum_{k=1}^{K} (\beta_k \cdot x_{ijk}) + \epsilon_{ij}, \tag{1}$$

where β_k is the preference coefficient for attribute *k*, x_{ijk} is the *k*-th attribute of alternative *j* subject *i*'s choice task, *K* is the number of observed attributes of alternatives, and ϵ_{ij} is the random error term, taken as an i.i.d. standard Gumbel distribution (8). Multicollinearty can be a concern with the market data, but we observe that all variance inflation factors (VIF) of all three explanatory variables—price, watt, and type—are smaller than five. (9)

Considering the large data size and time taken for model estimation, we use a multinomial logit model instead of a mixed logit (i.e. random coefficient) model. As in Min *et al.* (6), we test the influence of both alternative-specific and customer-specific attributes on purchases of general service light bulbs. We control for customer-specific attributes provided by Nielsen: household income, type of residence, education, and marital status. In addition, we test the effects of other exogenous factors that may have affected sales purchases: the effect of retail channel types, the effect of a key retailer, and time effects. The time effects need to be considered because important events like the enactment of the EISA in 2007 which is unobserved in the data could have affected purchase behaviors. Also we consider the effect of CFL promotion by Wal-Mart.

It should be noted that the rated-lifetime information of a product was not available in our dataset, and is confounded with the type variable, as CFLs and incandescent bulbs have very distinct ranges of product life. The type of light bulb may also be correlated with the color temperature as CFLs have generally a wider range of colors than incandescent ones. We recognize these confounding factors when interpreting the coefficients. Brightness is also unobserved in the original data, which is correlated with wattage levels. To accommodate this issue, an interaction term between type and wattage is included in the model estimation. This can be justified by an observation shown in Figure 1 that the two different lighting technologies show very different ranges of luminous efficacy (lumen output per watt).

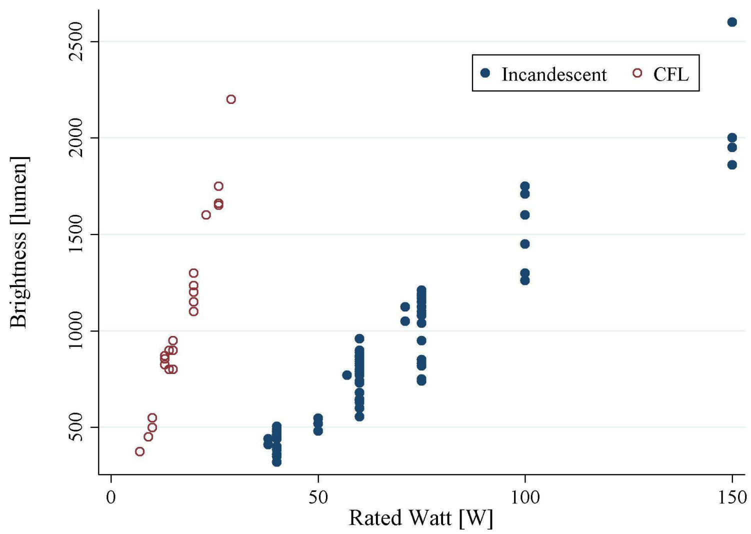

Figure 1. Relationship between rated wattage and brightness (in lumen) of all general service light bulbs observed in Nielsen data.[1] Each dot is for a light bulb product observed in the data.

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[1] For about 5% of the light bulb items observed in the panel data, we could acquire technical details including lumen, life, socket type, etc. through combining product data collected from online stores. Figure 1 shows the relationship between watt and lumen attributes for those 5% of bulbs. The relationship appears linear, and can be estimated from:

$$Lumen = -186 + 167 \cdot d^{\mathrm{CFL}} + 16 \cdot watt + 46 \cdot d^{\mathrm{CFL}} \cdot watt,$$

where d^{CFL} is 1 for CFLs and 0 otherwise.

Brand is separately coded as dummy variables for three major manufacturers: General Electric, Sylvania, and Philips. There are many other brands which are either store-specific or with small market share. They are treated together as a reference case for brand comparison. For the model with additional variables, the influence of retailer types, income level, residence type, and education level are tested.

Choice set selection issue

An important issue occurring from using sales data is that researchers do not have information on alternatives that were also available but not selected by consumers. Ideally, we would like to know the exact set of products that the consumer considered when making her final decisions. This set of alternatives is called a “consideration set” or a “choice set” in consumer choice literature (10). Attribute values of alternatives in the choice set are required for the estimation of a choice model. Since these are not available for our analysis, various assumptions need to be adopted to construct an assumed choice sets.

One source of information that we can use to estimate the consideration set is the information on purchases from other consumers, made in the same or nearby stores, and around the same time. We construct a choice set through this method by combining UPC observations from the available data. This requires the modeler to pursue decisions regarding the scope of UPCs to include in a consideration set. For example, the choice could include all purchased UPC observations ranging from across all retail chains or only from each individual chain where the observation is purchased. It could include all UPCs sold in each month or in a longer period of time, such as an entire year. In addition, the geographical scope could range from a choice set at the level of the entire nation or within each region (east, west, south, or central). In a nutshell, the choice set will require considerations in terms of the time span, geographical region, and store type. The process of how we estimate the choice set is explained in the next section.

When considering whether products from one or many store chains should be included in the choice set, the implicit issue that arises is whether we can assume that a consumer considers what to buy first and then decides where to visit to find the item, in which case the consumer’s consideration set is wider and not limited to a specific retailer store. For this purpose, we observe percentages of total expenditure spent on light bulbs at each shopping trip involving any light bulb purchases. If consumers normally choose from items displayed in a store where they visit to purchase some other products, we assume the relative percentage of spending on light bulbs when compared to all purchases is low.

The average of the percentage of total expenditure spent on light bulbs is 14%, and the median is 6%. The 75% percentile is 15%, which means that for 75% of all shopping trips involving light bulb purchases, money spent on light bulbs takes less than 1/7 of the total. The distribution of these percentage values is shown in Figure 2 for the shopping trips where consumers purchased light bulbs. This observation, though incomplete, can support the notion that consumers consider which bulb product to choose after, not before, they arrive at a store. Based on this finding, we choose to construct the base case choice sets for each retailer chain.

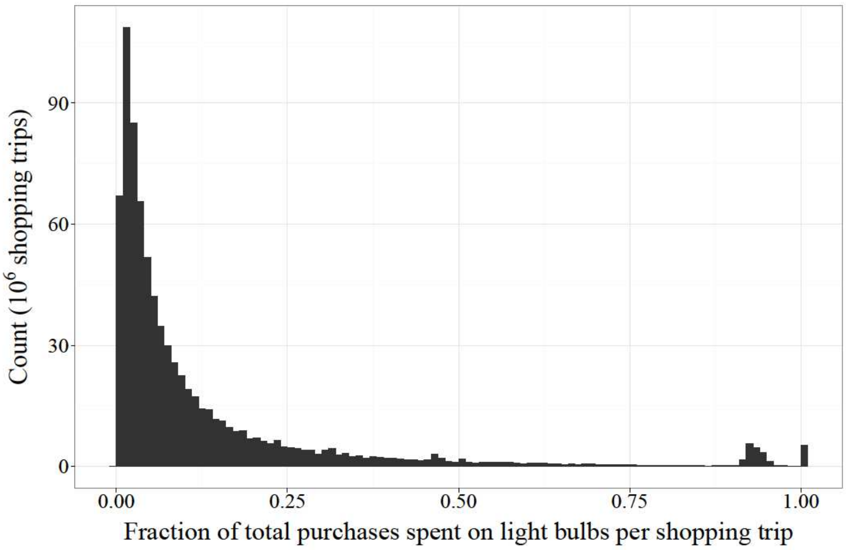


Figure 2. Distribution of percentage of total expenses spent on light bulbs at each shopping trip. This plot is only for the shopping trips involving light bulb purchases. The mean is at 0.14, and the median is 0.06. We can also observe at the right end that there are a small number of shopping trips mainly intended for light bulb purchases.

The items available in a store vary over time (from year to year, or from month to month, for example). One could then assume that the choice set should be constituted from all items sold in a month, or all items sold in a year. We decide to use a monthly choice set for the main model partly because we assume store items vary at least seasonally and also because the finding from Figure 2 suggests that people may not be able to consider items that were available months ago for a current purchase choice. However, it can be problematic as the monthly choice sets may include very few purchases, especially when the purchases are from small retailers, and therefore leading to a very small consideration set. When any monthly choice sets end up with only one UPC observation, we extend the consideration set for that retailer to include UPCs purchased during the whole year.

Another issue is whether stores of an identical retailer chain maintain similar set of items across the country, or whether products will vary by region. In order to account for this issue, we use a regional choice set, considering that products may vary by region at stores of a national chain.

Finally, in several instances, the same UPCs purchased within a given boundary may have a different price in different stores or as a result of a deal. Because it is not realistic for consumers and does exacerbate the IIA issue[2] to have two identical products with two different price levels available in the same store at the time of their choices, we need to pick one among repetitive UPCs appearing in a choice set. We test two approaches to tackle this issue: 1) using the most common price level observed in the data for that UPC, or 2) use a random price selection based on equal probabilities assigned to each observed sale. The second method still gives a higher probability to a more common price level because the level appears more frequently in a choice set. There is no clear way to justify one way or the other. We decide to use the random method as a base case and observe how using the other affects the result.

Table 2 summarizes the discussion in this section about the selection process of the choice set.

[2] A multinomial logit model, by its formulation, needs to assume the independence of irrelevant alternatives (IIA), which means the ratios between choice probabilities for any two alternatives in a choice set are preserved when another alternative is added to the set.

Table 2. Summary of choice set selection process

Issue	Dimension	Option	Choice	Justification
Which boundary to use to construct choice sets	Geographical boundary	State-/county-level	x	State- or county-level considerations cannot be considered because sample weights in the data can only be used to represent population at the regional or national level. Then we assume stores of an identical retailer chain can maintain different set of items across regions.
		Regional	o	
		National	x	
	Time span	Month	o	We assume items in stores can vary monthly or seasonally. Shoppers may not be able to consider items that were available months ago for a current purchase choice.
		Year	x	
	Store chains	All chains	x	We observe the average percentage of shopping expenses spent on light bulbs is low. We assume that this means consumers choose from items displayed in a store where they visit to purchase other products.
		Individual chain	o	
How to select a price level for identical UPCs in a given choice set		Most common price	x	One is not necessarily more justifiable than the other. We pick the random method as a base case which is simpler to implement and faster to run and test how using the other affects the result.
		Random pick	o	

Comparing stated and revealed preferences

In Min *et al.* (6), we conducted a choice-based conjoint experiment for incandescent and compact fluorescent bulb choices to quantify the influence of factors that drive consumer choices based on the stated preference. We showed that providing operating cost information at the time of choice reduces consumers' implicit discount rate significantly, which will increase the adoption of energy efficient products.

Here, we compare the previous findings from Min *et al.* (6) with those from the consumer panel data. (Hereafter, the former will be referred to as the stated preference (SP) model, and the latter as the revealed preference (RP) model.) We mainly compare willingness-to-pay (WTP) for light bulb attributes (watt and type) and implicit discount rates (IDR) consumers adopt for their purchases.
For the ease of interpretation of derived WTPs, we estimate multinomial logit (MNL) models from both SP and RP data with only the main effects of the available bulb characteristics and a brightness term constructed from wattage and type variables.[3] Because the types of collected data are different between the two datasets, we cannot fully compare models based on the identical specification used in the SP model. The RP model for the WTP estimation is:

$$U_{ij} = \beta_1 x_{ij}^{\mathrm{PRICE}} + \beta_2 x_{ij}^{\mathrm{WATT}} + \beta_3 x_{ij}^{\mathrm{TYPE}} + \beta_4 \hat{x}_{ij}^{\mathrm{BRIGHT}} + \beta_5 x_{ij}^{\mathrm{PKGSIZE}} + \epsilon_{ij}. \qquad (2)$$

To compare the estimates of implicit discount rates (IDR), we use a similar nonlinear model specification suggested in Min *et al.* (6), which is:

$$U_{ij} = \beta_1 \left(\frac{\beta_2 (1+\beta_2)^{x_{ij}^{\mathrm{LIFE}}}}{(1+\beta_2)^{x_{ij}^{\mathrm{LIFE}}} - 1} x_{ij}^{\mathrm{PRICE}} + x_{ij}^{\mathrm{OPCOST}} \right) + \beta_3 x_{ij}^{\mathrm{TYPE}} + \beta_4 x_j^{\mathrm{PKGSIZE}} + \epsilon_{ij}, \qquad (3)$$

where the term within parentheses means equivalent annual cost, and β_2 directly represents the average discount rate which consumers implicitly adopt for their comparisons. Since life is not observed, we need to assume additionally that all CFLs constantly have 8000 hours of life (about 7 years assuming 3 hours of use/day) and incandescent lamps have 1000 hours of life (about 1 year).

[3] Brightness $\hat{x}_{ij}^{\mathrm{BRIGHT}}$ is estimated through the equation in Footnote 1.

We also assume 10¢/kWh for average residential electricity price for the period between 2004 and 2009 to estimate the annual operating cost of each bulb.

Results and analysis

Market characterization

Figure 3a shows the sales by UPC from 2004 to 2009. The plot shows the top 100 bestselling UPC items among the 2,490 UPCs. These 100 items account for about 60% of all sales from 2004 to 2009.

Figure 3b shows sales from the top 50 retailer chains in terms of number of light bulbs sold. There are a total of 640 distinct retail chains identified by the retailer ID field in the data. The top 50 retailers shown in Figure 3b sold 87% of all general service light bulbs. Just the top five retailers account for 43% of sales. We note that the top selling retailer chain is a discount store that is selling about three times the sales of the second retailer, which is also a discount store. Examples of discount stores are Wal-Mart, Target, and Kmart.

Figure 3c and 3d are drawn separately for incandescent bulb and CFL sales respectively. The 1st place retailer chains in Figure 3b, 3c, and 3d have an identical retailer ID. Although the Nielsen data only reveals the codified IDs of retailers, we can speculate who the most dominant retailer is from other available information. From an online UPC search service provided by international standards organizations such as GS1 (11), we find that many among the bestselling UPC values from the top seller are the ones assigned to Wal-Mart.[4] From this, we infer the top bulb seller is Wal-Mart. We see that light bulb sales are highly concentrated to a few large retailer chains headed by Wal-Mart.

Figure 4 shows trends of light bulb purchases and average price per bulb. The total light bulb sales decrease over time while CFL sales peaked in 2007 and decreased afterward. Potential reasons for the peak can be either the enactment of the Energy Independence and Security Act (EISA) or the nationwide CFL campaign by Wal-Mart in 2007 as explained in the introduction. The total sales decrease can be due to the longer lifetime and lower turnover rate of CFLs or the economic plunge starting from 2008. While average price paid by customer for an incandescent bulb kept increasing slowly ($0.36 in 2004 to $0.45 in 2009), CFL price almost monotonically decreased from $2.77 in 2004 to the lowest ($2.02) in 2008 but slightly increased in 2009.

The peak in CFL sales in year 2007 could be driven by either change of consumer preferences or change in product availability because manufacturers react to the new regulation or other changes in the business environment. Figure 5a shows the number of unique UPC items each year for the two technologies. The number of CFL items increased over the six years, while the number of incandescent items stayed almost at a constant level. Figure 5b is for the changes in the stock for each type. The bar graph displays the number of the new or retired UPCs in each year for each type. We see that the number of newly introduced CFLs rapidly increased especially in 2009. This observation suggests that manufacturers emphasized new efficient lamp products. We also assessed the total number of unique producer codes, which is identifiable from the first six digits of UPC, and found that the number of CFL manufacturers notably increased after 2007. There have been around 20 brands or companies manufacturing CFLs until 2007 but the number increases to 35, 46, and 58 in 2007, 2008, and 2009 respectively.

[4] However, this method does not work for other retailers who do not have custom brand items.

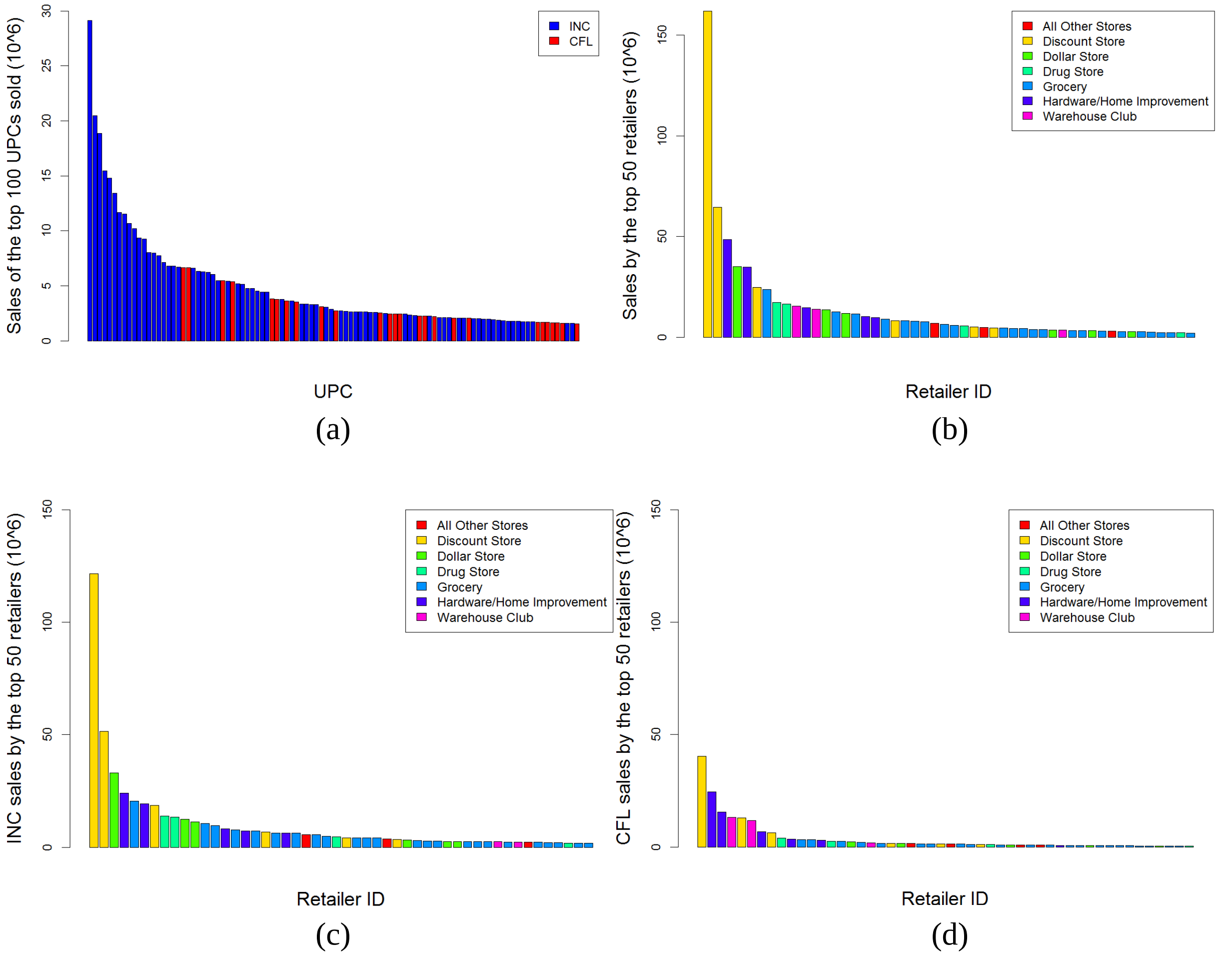


Figure 3. (a) Histogram of light bulb package sales by product code (UPC) for the top 100 selling bulb products from 2004 to 2009. UPC codes corresponding to incandescent lamps are showed in blue, and compact fluorescent lamps UPC codes are shown in red; b) Histogram of light bulb sales by for the 50 retailer chains with the largest number of sales from 2004 to 2009, by retailer type; c) Similar histogram only for incandescent bulb sales by retailer type; d) Histogram only for CFL sales by retailer type.

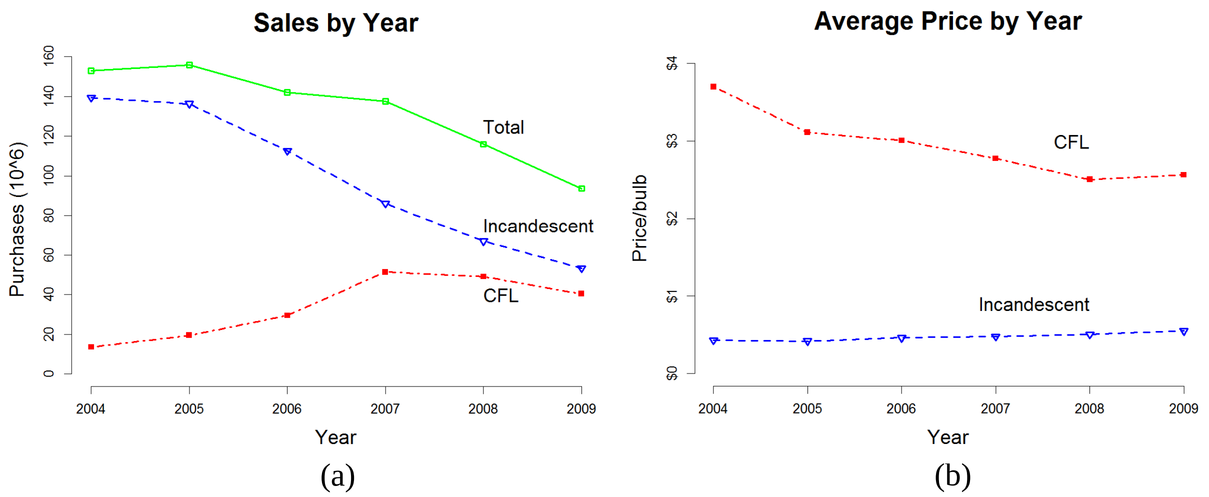
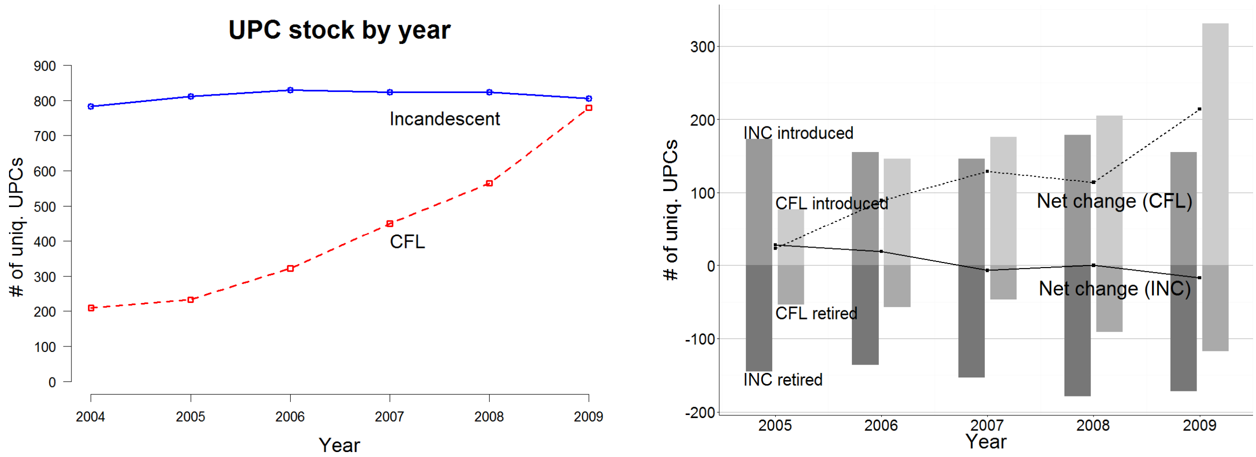


Figure 4. (a) Quantity of incandescent lamps and CFLs sold each year, scaled by weighting factors to provide a nationally representative sample; (b) Weighted average prices for incandescent lamps and CFLs from 2004 to 2009.

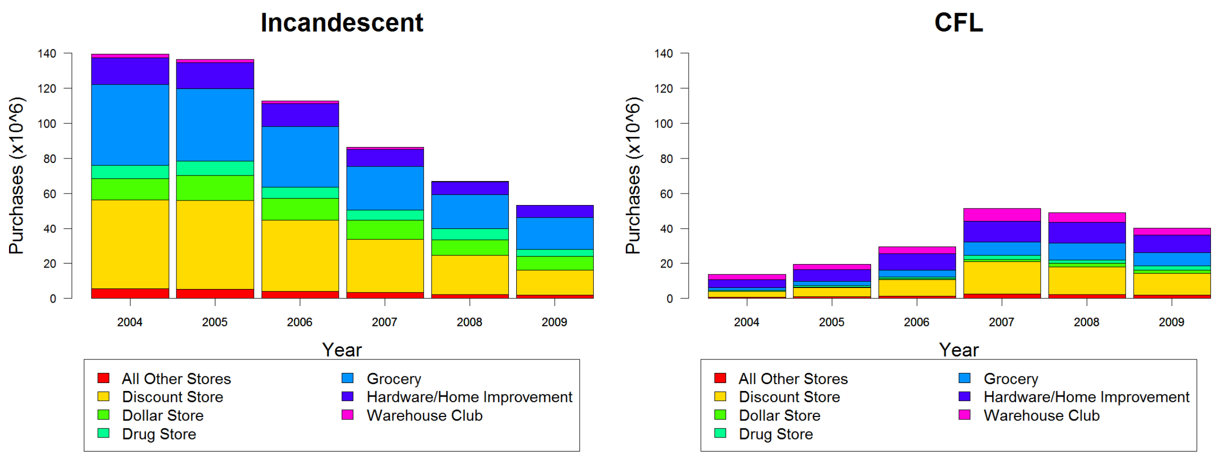


(a) (b)

Figure 5. Sales and price trends of each light bulb type during 2004-2009. a) Total number of unique UPCs per year; b) Number of unique UPCs introduced and retired each year. The bar graphs are for the total number of introduced or retired UPCs each year. The lines show net changes in number of unique UPCs.

There are 640 distinct retailer chains that sold light bulbs between 2004 and 2009. The sales distribution across store types is shown in Figure 6. The sales values are weighted by the weighting factor. The distributions are very distinct between CFLs and incandescent bulbs. Incandescent bulbs are bought predominantly at discount stores and grocery stores, while a majority of CFLs are bought in hardware stores, warehouse clubs, or discount stores. Warehouse clubs play a very important role in CFL sales while they are nearly negligible for incandescent bulb sales.

The numbers of distinct chains under each retailer type are shown in Table 3. We see that while grocery chains are the largest seller of incandescent bulbs in total according to Figure 6a, sales from each grocery chain will be small when divided by the large number of grocery chains in the data. On the other hand, average sales per discount or hardware store chain will be large since there are not many distinct chains.



(a) (b)

Figure 6. Breakdowns of light bulb sales by store types. a) Incandescent bulbs; b) CFLs.

Table 3. Number of distinct retail chains that sold light bulbs between 2004 and 2009.

Type	Discount Store	Dollar Store	Drug Store	Grocery	Hardware Store	Warehouse Club	Other	Total
Number	15	13	29	380	12	6	185	640

Figure 7 shows the number of unique UPC items purchased in each store type each year across the country. Because this is for each retailer type, the same UPC can be counted in more than one retailer types. While grocery stores appear to have the widest variety of incandescent bulbs, again it is potentially because there are many more grocery stores than hardware or discount stores, as shown in Table 3. Consistently with Figure 5, counts of incandescent bulb UPCs at each store type did not decrease significantly over time, while counts of CFL UPCs constantly increase. This suggests that the manufacturers are not phasing out incandescent bulbs ahead of the EISA of 2007 taking effect in years to come.

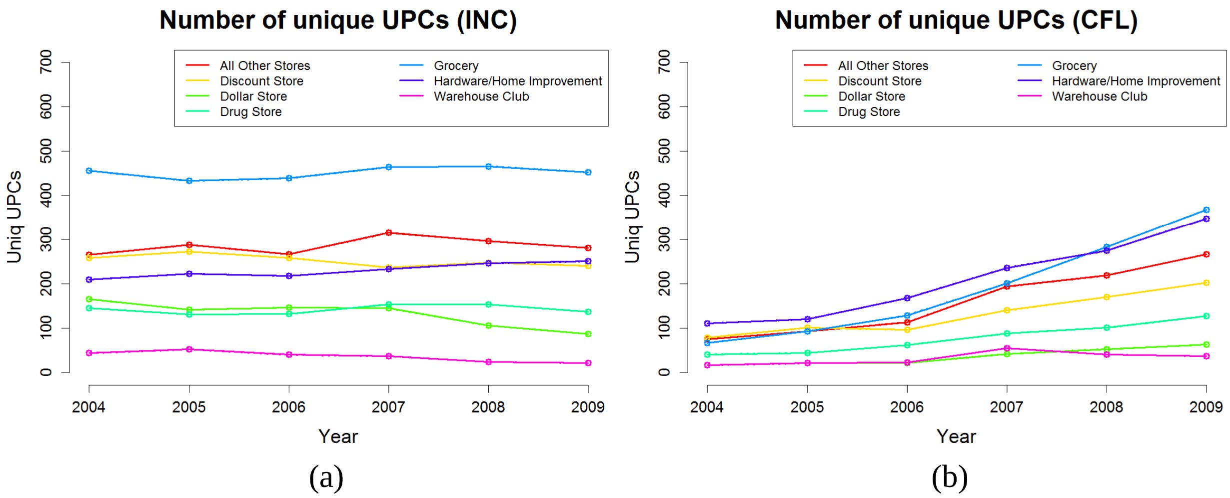


Figure 7. Number of unique UPCs sold at each store type. a) Incandescent bulbs; b) CFLs

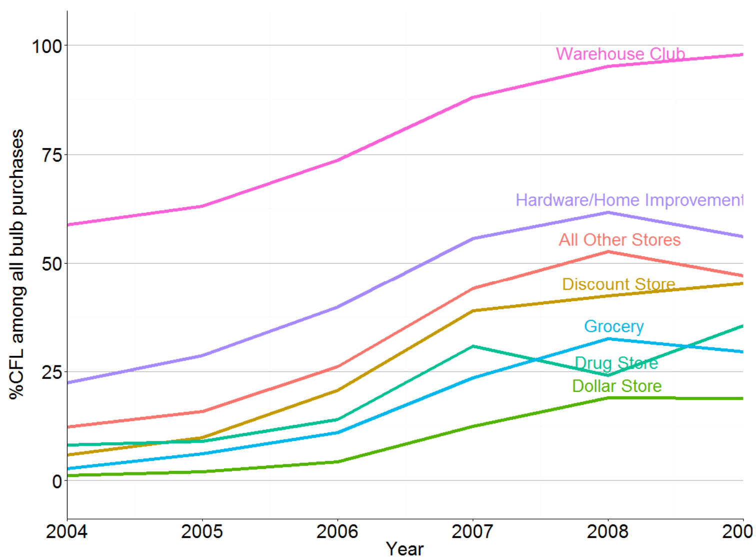


Figure 8. Trends of percentage of CFLs among all general service bulb purchases from each store type.

Representative region-level trends are shown in Figure 9. Each of the eight different areas is for each combination of region and type. The top four areas in lighter colors are for CFLs and the lower four in darker colors are for incandescent lamps. Figure 9a shows that CFL sales increased while incandescent lamp sales decreased. Total lamps sales are highest in the South region mainly because it has the largest population. Figure 9b and 9c represent annual electricity consumption and carbon emission from the bulbs purchased within each year. To calculate the electricity consumption, we adopt daily hours of use (HOU) per type of bulb in each region from DNV KEMA (12). According to this report, the daily HOU of incandescent lamps is normally between 1.2 and 1.3 hours/day, while that of CFLs is between 1.8 and 2.0 hours/day. Regional emission factors for each year are based on state-level emission factors adopted from eGRID (13). But since eGRID does not have emission factors for every year, we used the previous year's values for the year for which eGRID data are not available. CO_2 emission factors have decreased over time in all regions. Figure 9d shows lumen-hours produced each year from the new lamps.

Figure 9 shows that total sales gradually decrease over the period in all regions as we also observed above. The magnitude of decrease is largest in the South region, where the most CFLs were sold over the years. While CFLs consume much less electricity and emit less CO_2 than incandescent lamps (Figure 9b and 9c), they generate even more lumen-hours after 2007 according to Figure 9d. Due to increasing adoption of CFLs, newly purchased light bulbs contribute to lowering carbon emissions and electricity consumption during the period, while not sacrificing lumen-hours as much.

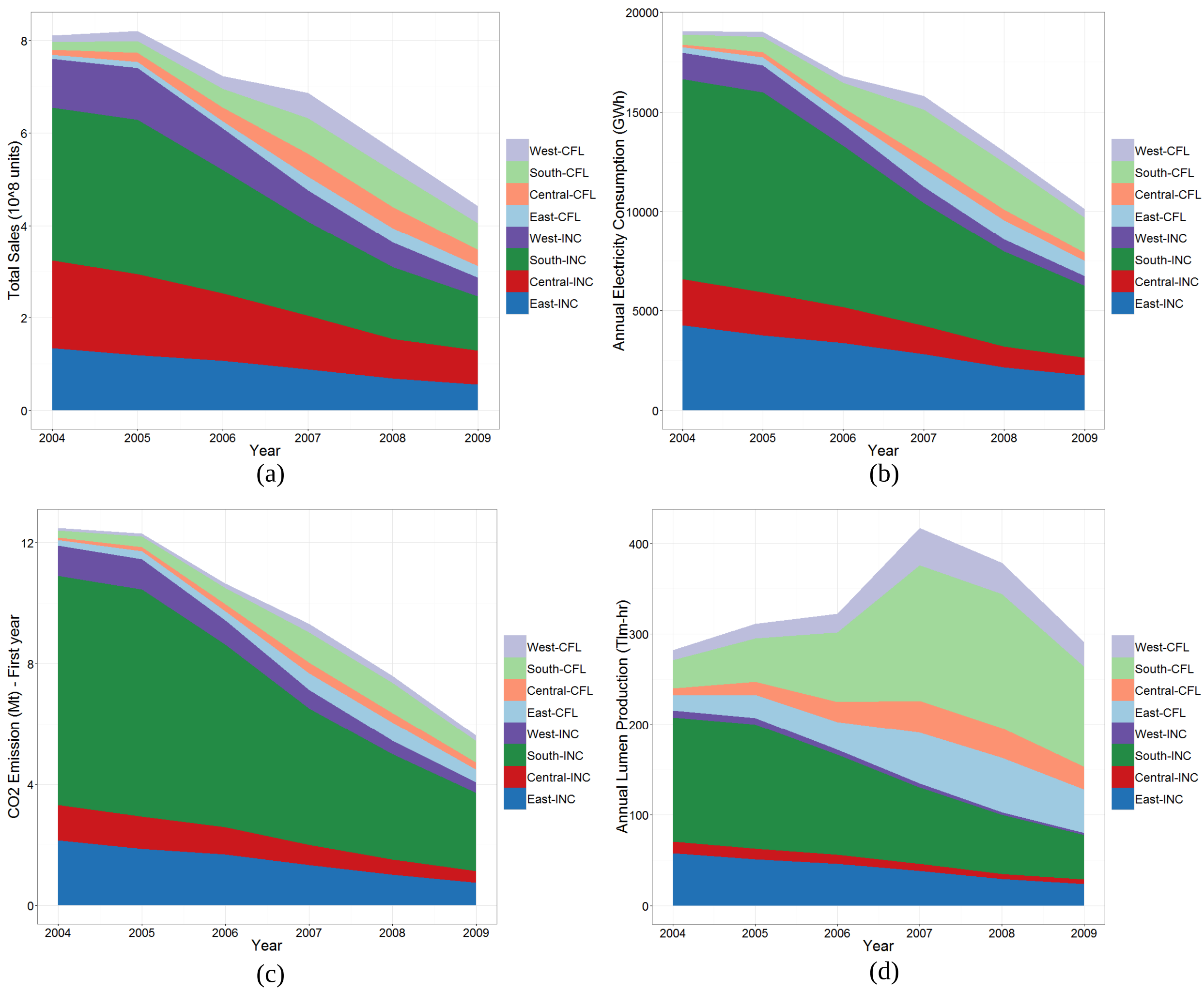


Figure 9. Light bulb sales, electricity consumption, lumen production, carbon emission by type, region and year. a) Total sales; b) annual electricity consumption; c) annual CO_2 emission ; d) annual lumen production. Areas with lighter colors are for CFLs, while darker areas are for incandescent bulbs. Similar colors identify different regions.

Understanding consumer choices for lighting technologies

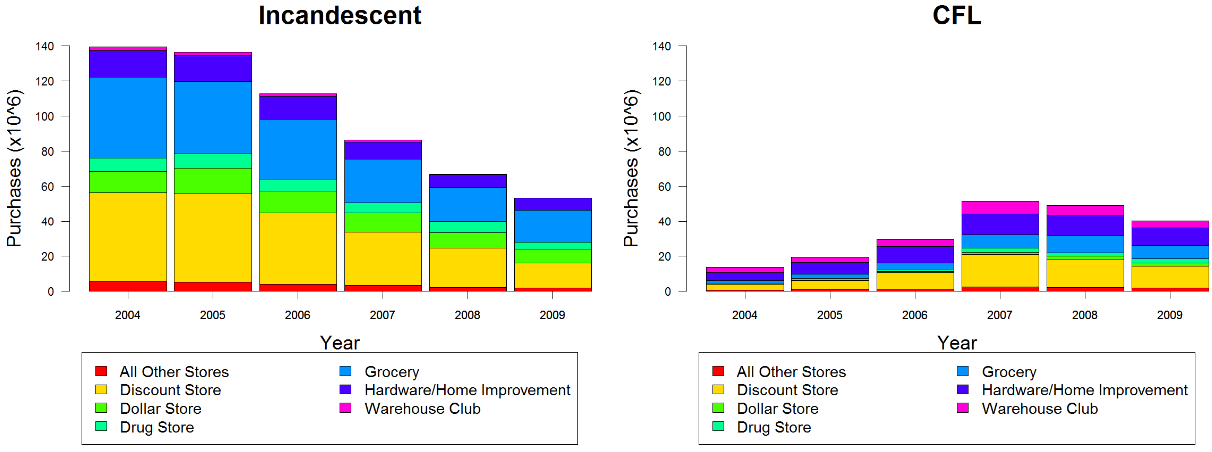
Based on the narrow choice set, we estimate a multinomial logit model testing effects of attributes that potentially affect preferences for lamp technology type. Based on the observations from above, our main model controls for time and regional effect, retailer types, effect of promotion by a key retailer (i.e. Wal-Mart), and other available demographic information. In the main model, a dummy variable indicating CFLs sold in Wal-Mart is included and interacted with year dummies. The motivation behind this is that if interest in CFLs generally increased in 2007, it would not influence choices of CFLs specifically from Wal-Mart.

The main model in Table 4 shows that the CFL type is preferred in the base case when all other attributes are kept constant. This can be partly because the type variable in the data is confounded with unobserved life and color attributes. Also, even though the coefficient for CFL type is positive, CFLs are not always preferred mainly because of higher price.

Wattage attribute is observed with a negative coefficient suggesting that consumers prefer lower energy consumption, while the interaction term between wattage and type showing the effect of brightness is not statistically significant. The SP model in Min *et al.* (6) showed that there is a statistically significant quadratic relationship between brightness and consumer utility, which suggests that the fact that the linear interaction term is not significant does not necessarily mean consumers do not consider brightness for their choices. The size of the interaction term (0.00135) is a lot larger than the coefficient for wattage attribute (-0.000647), which suggests that consumers may prefer higher wattage for CFLs and lower wattage for incandescent bulbs. This is understandable considering that lower luminous efficacy of incandescent bulbs means that more power (i.e. higher energy bill) yields a relatively smaller amount of light, which sums up to a net negative utility. On the other hand, for CFLs, the same increase in power means a large increase in light output, which will turn out as a net positive utility. CFLs from major manufacturers are preferred to those from other smaller manufacturers.

We observed earlier that CFL sales peaked in 2007. The main model shows that the overall preference for CFLs over incandescent lamp types gradually increased from 2005, peaked in 2007, and significantly dropped in 2008 and 2009. Preference toward CFLs from Wal-Mart increased very steeply in 2006 and 2007 and appears to stay near the peak level for the next two years. This suggests that the promotion of efficient bulbs by Wal-Mart in 2007 may be significantly related to the spike in CFL adoption in 2007 in addition to an increase in general awareness of CFLs and also that the effect is sustained even after the promotion ends. Several issues may be playing a role in decreasing CFL sales observed: since CFLs last longer, fewer purchases are needed over time to maintain the same lighting service. Or CFLs may already have filled a large part of the sockets that consumers intended to use CFLs in. Also, the EISA 2007 or other events around 2007 raised interests in CFLs, but over time consumers may have lost the interest in CFLs and looked for inefficient bulbs again.

The main model in Table 4 shows that among the six major channel types, as we could expect from the sales trend by channel types in



(a) (b)

Figure 6, CFL type is preferred in hardware stores and warehouse clubs significantly more than in discount stores. In dollar stores, drug stores, and groceries, incandescent types are preferred.

Among demographic variables, households whose heads have a bachelor's degree prefer the CFL type more than those who have not. Also, when compared with the lowest income households (<$20k/year), those with higher income (<$100k/year) prefer CFLs. But households with even higher income (>$100k/year) are not significantly different from the lowest income group. We observe that lower preference for CFLs is also related with a larger household size and whether they live in single-family houses. A potential explanation for this can be that households requiring more light bulbs prefer incandescent bulbs because of lower initial costs while not taking into account future operating cost savings.

Table 4. Coefficients and variance derived for the main model including all relevant variables. The narrow choice set is assumed.

	β	σ
type=CFL	0.415	(0.0739)***
price_paid_per_bulb	-0.284	(0.00473)***
watt_nielsen	-0.000647	(0.000147)***
(type=CFL)*watt_nielsen	0.00135	(0.00113)
size1_amount	0.0140	(0.00143)***
base brand: Other		
GE	-0.273	(0.0106)***
GE_cfl	0.399	(0.0205)***
Philips	-0.525	(0.0203)***
Phil_cfl	0.322	(0.0428)***
Sylvania	-0.431	(0.0182)***
Syl_cfl	0.266	(0.0273)***
base year: 2004		
type=CFL & panel_year=2005	0.222	(0.0444)***
type=CFL & panel_year=2006	0.298	(0.0445)***
type=CFL & panel_year=2007	0.419	(0.0382)***
type=CFL & panel_year=2008	0.276	(0.0399)***
type=CFL & panel_year=2009	0.0953	(0.0416)**
WalMart_CFL	-0.706	(0.0854)***
WalMart_CFL & panel_year=2005	-0.235	(0.0974)**
WalMart_CFL & panel_year=2006	0.150	(0.0921)
WalMart_CFL & panel_year=2007	0.420	(0.0845)***
WalMart_CFL & panel_year=2008	0.366	(0.0865)***
WalMart_CFL & panel_year=2009	0.361	(0.0910)***
household_size*type=CFL	-0.123	(0.00693)***
base channel: Discount Store		
(major_channels=Dollar Store)*type=CFL	-0.452	(0.0514)***
(major_channels=Drug Store)*type=CFL	-0.222	(0.0492)***
(major_channels=Grocery)*type=CFL	-0.189	(0.0381)***
(major_channels=Hardware/Home Improvement)*type=CFL	0.333	(0.0379)***
(major_channels=Warehouse Club)*type=CFL	0.599	(0.0531)***
base marital status: Married		
(marital_status=Widowed)*type=CFL	0.0824	(0.0310)***
(marital_status=Divorced)*type=CFL	-0.0395	(0.0246)
(marital_status=Single)*type=CFL	-0.0405	(0.0257)
(region=Central)*type=CFL	0.0101	(0.0257)
(region=South)*type=CFL	-0.00294	(0.0249)
(region=West)*type=CFL	-0.0528	(0.0308)*
base type of residence: Mobile		
(type_of_residence=Multi-family)*type=CFL	-0.0801	(0.0452)*
(type_of_residence=Single-family)*type=CFL	-0.0958	(0.0370)***
(type_of_residence=Two-family)*type=CFL	-0.0534	(0.0571)
(bachelor=1)*type=CFL	0.0974	(0.0186)***
base income bracket: <$20k		
($20k<household_income<=$40k)*type=CFL	0.121	(0.0288)***
($40k<household_income<=$60k)*type=CFL	0.160	(0.0307)***
($60k<household_income<=$100k)*type=CFL	0.146	(0.0317)***
($100k<household_income<=$200k)*type=CFL	0.0299	(0.0366)
(household_income >$200k)*type=CFL	-0.131	(0.0942)
Observations	7,130,802	
Log-Likelihood	- 1.810e+09	

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Comparing two choice models based on revealed and stated preference data

Willingness to pay

We estimate WTPs from SP and RP data using MNL models including only the main effects of light bulb attributes to derive population average WTPs. To control for the effect of unobserved brightness information in the RP model, we include brightness values estimated from the relationship shown in Figure 1 and Footnote 1 instead of the interaction term between type and wattage which was originally used for the main model in Table 4. This is because having the estimated brightness term enables easier interpretation of the result. The result is summarized in Table 5.

Table 5. Comparison of willingness-to-pay for changes in two main attributes: lamp type and wattage when all other attributes are held constant. RP and SP represent revealed and stated preference data. We should note that because of confounding between observed and unobserved attributes, the WTP-RP value for lamp type is likely to represent combined WTPs for type and all correlated changes (e.g. life or color). WTP-SP values are from Min *et al.* (6).

		WTP - RP		WTP - SP	
Attribute	Δ(attribute)	Mean	95% CI	Mean	95% CI
Type	CFL over incandescent	\$1.84	(1.68, 2.00)	\$2.37	(1.57, 3.18)
Wattage	10W increase	-\$0.06	(-0.08, -0.03)	-\$0.37	(-0.51, -0.24)
Brightness	100 lumen increase	\$0.02	(0.00, 0.033)	\$0.16	(0.10, 0.23)
Life	1000 hour	N/A[a]		\$0.50	(0.38, 0.62)
Color	CCT=3700K or 5000K (base=2700K)	N/A[a]		Not significant	

[a] Life and color data were not available in the RP dataset, and these attributes may be confounded with type, watt, or brightness.

We should note that because of the unavailability of life and color attributes in the panel data, the WTPs for lamp type change in the SP and RP case are not directly comparable. The RP model suggests that consumers are willing to pay \$1.84 more for a change from an incandescent bulb to a CFL, holding watt and brightness constant. However, there may be other attributes, such as life and color, that are correlated with type but for which we lack data. Thus the WTP for type in the RP data captures the effect of type plus these potentially correlated attributes. A separate WTP value only for the lamp type cannot be derived from the panel data. The WTP for the CFL type in the SP model was \$2.37. In this case, because all other attributes observed by the respondent are known and controlled for, the value represents the WTP for lamp type alone, holding all other attributes in the experiment constant (including wattage, brightness, life, and color). The fact that the WTPs for the CFL type is positive does not mean consumers always choose CFLs over incandescent lamps because these WTP estimates assume all other attributes are constant. In real choices, the price difference between a CFL and an incandescent lamp can easily be larger than the WTP for a CFL type. For the wattage variable, a WTP for 10W increase is -\$0.06 for the RP model, while the corresponding WTP for a 10W increase for the SP model was observed at -\$0.37. These negative WTP values mean that consumers prefer lower wattage when all other attributes are equal.

From the findings above, it appears that the stated preference (SP) model yields consistently larger WTPs (in absolute magnitude) than the revealed preference (RP) model does. A potential reason is that the price coefficient in the SP model is underestimated because the compensation given at the end of the experiment depended on a choice made in an unknown choice task during the choice experiment, which might well induce participants to behave less sensitively to price variable in order to receive more expensive item as the compensation.

Implicit discount rate

To reduce the computational burden, we focus on a representative state within each region for implicit discount rate (IDR) comparison. To justify this approach, we test a model without weighting factors using the same model specification of the model in Table 4. Even though the weighting factors in the Nielsen data cannot be used to represent state-level population, we see that the model *without* weighting factors yields results which are close to those estimated from the model *with* weighting factors. Based on this observation, we present state-level model outputs, while not worrying about representativeness.

From the Central, West, and South region, we pick Ohio, California, and Texas because these states have the largest number of observations in the panel data. For the East region, we choose Pennsylvania partly because it has the second largest number of observations and also because our SP model is also based on the experiment performed in Pittsburgh, Pennsylvania. The result is summarized in Table 6. We see that the ranges of discount rate values from the two different datasets are comparable, suggesting the results are robust. Detailed model results used for IDR estimation is given in Table 7. The IDR values for stated preference data shown in the last two columns are directly from Min *et al.* (6).

Table 6 Comparison of estimates of implicit discount rates based on revealed and stated preference data

	Revealed Preference				Stated Preference	
	Pennsylvania	California	Texas	Ohio	Operating cost shown	Operating cost not shown
Implicit discount rate	260% (0.3%)	330% (0.1%)	230% (0.5%)	290% (0.9%)	100% (22%)	560% (70%)

Standard errors in parentheses

Table 7 Models for implicit discount rate (IDR) estimation. Each column is for a representative state from each region.

	East - Pennsylvania		West - California		South - Texas		Central - Ohio	
	β	σ	β	σ	β	Σ	β	Σ
Equivalent annual cost	-0.042	(0.00019)***	-0.043	(0.0017)***	-0.12	(0.00028)***	-0.085	(0.00021)***
Implicit discount rate	2.58	(0.0028) ***	3.32	(0.0011)***	2.26	(0.0054)***	2.85	(0.0089)***
type=CFL	-0.092	(0.0013) ***	0.17	(0.0016)***	-0.29	(0.00069)***	-0.15	(0.00042)***
Package size	0.013	(0.0011) ***	-7.0e-5	(0.0027)	-0.025	(0.000034)***	0.0063	(0.000020)***
Brightness ($\times 10^3$ lumen)	0.016	(0.0020) ***	0.025	(0.0019) ***	0.60	(0.00092) ***	0.46	(0.0021) ***
Purchase observations	15,417		21,100		33,235		21,439	
Log-Likelihood	-37,828		-50,749		-103,905		-60,487	

Standard errors in parentheses

All IDR estimates here are higher than 200%, suggesting that, during the observation period, the barriers to energy efficient lighting were considerably high. Among the four states, Texas exhibits the smallest IDR of 230%, while California has the largest of 330%. According to the panel data, California has the highest CFL adoption rate among the four states, which is about 40% of all bulb purchases between 2004 and 2009, while Ohio has the lowest rate of 25%. Thus, we observe that the differences in the adoption rates are not directly explained by the IDR estimates, which is possible when the bulb choices are determined more by other factors such as type preferences or price sensitivity than by expected savings.

All the IDR values sit between 100% and 560%, which are the two point estimates from the SP model shown in the last two columns of Table 6. One of the reasons for this finding can be that some light bulb packages were still providing annual operation cost information voluntarily between 2004 and 2009. This was likely to have an influence on bringing the IDRs between the level where 100% packages were assumed to have such information and the level where the cost information is not present at all. Moreover, subjects in the SP experiment could be less sensitive to monetary values such as future savings because of the hypothetical setup, and there are missing attributes that may be confounded with the attributes used to measure IDR.

Conclusions

We investigated trends of light bulb sales from an extensive consumer panel dataset spanning from 2004 to 2009 and analyzed consumer preferences for light bulbs based on revealed preference data. We focused on general service incandescent lamps and CFLs as defined in the EISA of 2007.

Total light bulb sales are observed to decrease almost monotonically over the period, while CFL sales increased until 2007 and then went down for two straight years afterward. The peak of CFL sales in 2007 is probably because of the enactment of the EISA of 2007 or the aggressive campaign by a key retailer in the same year. Within the period, new CFL products represented by unique UPCs are constantly introduced to the market increasing from about 200 items in 2004 to 800 items in 2009, while the number of distinct UPCs of incandescent lamps stays constant at around 800 during the period. We can conjecture that manufacturers are trying to adapt to the new market environment caused by the EISA of 2007. Even with the continuing variety of incandescent bulbs, constantly shrinking sales of incandescent lamps show that the market is transforming.

Light bulb sales are heavily concentrated to several key retailers, which can imply that efforts taken by these retailers can influence nationwide adoption of efficient lighting. Discount stores are where the most consumers go to buy light bulbs, while grocery stores are the second largest seller of incandescent bulbs, and hardware stores are the second for CFL sales. Across all retailer types we observed, CFL adoption was increasing almost consistently until 2008, while it slightly drops in hardware stores and groceries in 2009. CFL adoption rates vary by state and region, which means that the preferences are driven by combinations of certain geographically varying factors. These factors can be policies, demographics, electricity rate structures, etc. Further studies are needed to determine which factors are influential to the regional (or state-level) differences in adoption rate.

We found that consumers prefer lower price in general, but preference for wattage depends on bulb types (CFL or incandescent). At an identical price level, consumers prefer CFLs to incandescent bulbs, but the large price difference keeps CFLs from being purchased. We also observed that the peak in CFL adoption in 2007 was significantly related to the increase of CFL sales by Wal-Mart, which in turn could potentially be linked to its nationwide promotion campaign for CFLs the same year. From the findings, we can argue that the well-directed efforts through major retailers might have a significant effect on higher adoption of energy efficient lighting.

Although the estimates of willingness-to-pay for changes in type and wattage are not directly comparable due to the unobserved attributes in the panel data, we observed that the signs matched. The willingness-to-pay values for the CFL type over the incandescent one and for lower energy consumption were found to be positive when other attributes are held constant, which is consistent with the finding from the conjoint experiment.

The implicit discount rates estimated in four representative states were in a range from two to four hundred percent similar to the values from the conjoint experiment. The large size of discount rates indicates that barriers to energy efficient lighting carried on during the period we observed.

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Is Smart Lighting Energy Smart?

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Energy piano

Abstract

Smart LED lamps appear more and at the market. These lamps provide the consumer with higher welfare, better product quality and/or energy and economy savings. Actually, most attention is paid to the first type of smartness which is the topic of this paper.

The lamps are typically controlled by a smartphone app that enable the lamps can dim, change colour, shift to new scenes or programmed lighting changes over time. However, the lamps consume energy even when they are not in use. Often is also needed a separate energy consuming gateway for communication.to the lamps.

The first indicative measurements from Australia, Europe and USA show the standby functions drastically increase the lamp's total energy use and the standby energy can be larger than the energy used for providing lighting.

In the future, there might be dozens of wirelessly controlled lamps in a single home, which taken together could result in high standby power losses. Therefor the IEA 4E SSL Annex has launched a new study on the energy performance of smart wireless lighting. Examination of the lamps as well as the communication protocols and gateways are expected to provide an evidence base for making recommendations to the government. The indicative measurements show design improvements for smart lamps are certainly possible in order also to become more energy smart.

Introduction

Smart LED lamps have appeared at the market during the last years. The major part of these lamps provide better welfare by the ability to dim, change colour or make use of programmed scenes with gradual changes in the lighting. These smart lamps are wireless controlled by a smartphone app or a dedicated remote control.

The capability of wireless control has the consequence that when the lamp is not emitting light, it switches to a standby mode waiting for a signal from the end-user to switch-on again. In a more advanced system the lamps may also be serving as part of a local wireless network, in a more active energy consuming mode. This means that these lamps are also consuming energy when they are not emitting light. Besides this standby consumption for the lamp and/or the luminaire there is often an extra consumption for a gateway which is a communication unit. These gateways - also called connection hubs or bridges - provide wireless communication between the general network for other devices and the lamps communication using protocols such as Zigbee, 6LoWPAN or Bluetooth.

The IEA 4E SSL Annex [ref. 1] recognises that the market potential of smart lighting is extensive, once the platform enabling functionality has been established. Besides use in the home or at work, these smart lighting products can also be used in other applications such as museums, exhibition halls, shopping centres and supermarkets where the lamps might be used as WiFi nodes to help consumers with smart phones to navigate a building or find products in a store. For example, the interaction between the smart lights and smart phones could activate visual and aural information for self-guided museum tours or detailed product information in a store. The opportunities and applications are virtually limitless.

The risk that smart features may offset some of the energy-efficiency gains from switching to LED technology is the reason why the SSL Annex has started to study smart wireless lighting currently offered in the market, assess their energy use and the performance characteristics of these lamps and systems and evaluate possible appropriate measures to facilitate lower standby mode power consumption.

There are other smart lamp features that prolong the lamp life (thermal control) or ensure to maintain a constant flux by regulation of the drive current. These features do typically not include standby consumption only extra control in the active state. Finally, there is different kind of sensors often of too low quality build into lamps or luminaires or placed external which typically are used for energy saving and improvement of the economy for the user. These two groups of other lamp smartness are outside the scope of this paper.

Smart Lamp Communication

The smartness of the smart lamps is due to a user interface typically by use of a smart phone where the user can adjust the lighting e.g. the amount of light, the colour of the lighting, scene setting and programmed gradual change of the lighting. The communication from the smart phone or a dedicated unit is typically wireless provided by Wifi or Bluetooth or wired by Ethernet. The communication to the lamp often requires a lamp gateway

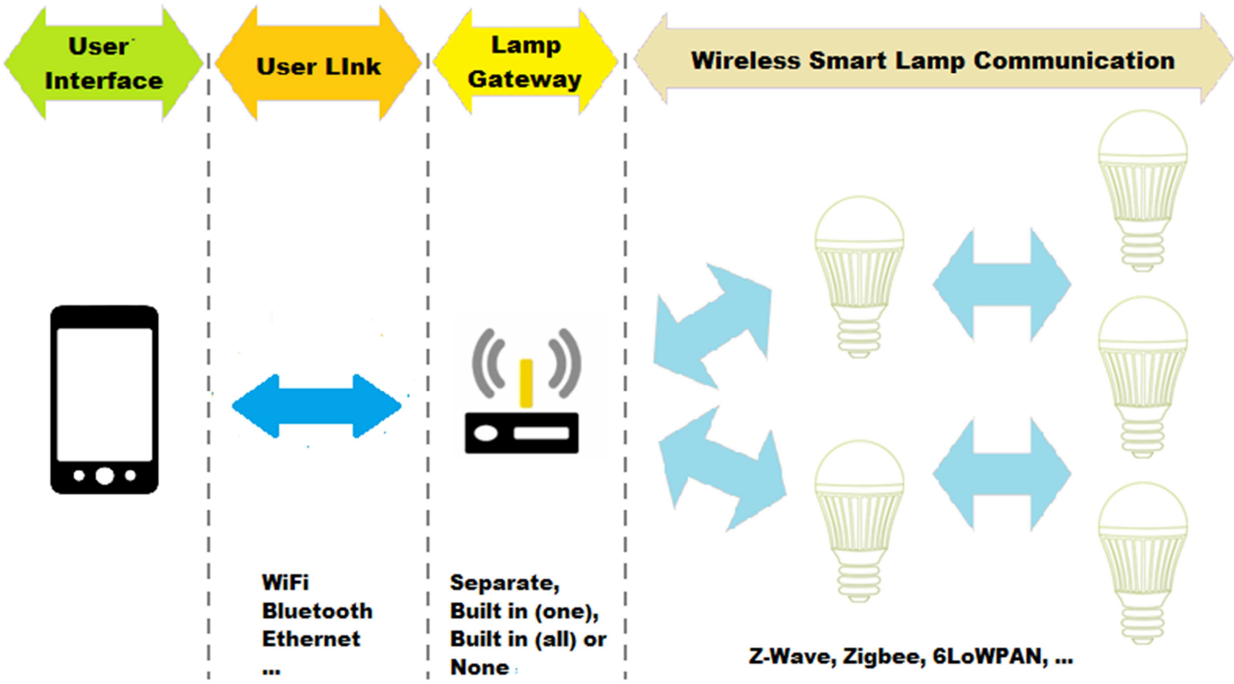

Figure 1 Smart lamp communication

There is often need for a lamp gateway to convert the communication used to access the lamps and for communication between the lamps. The lamp gateway is thus something different from the general WiFi router used in a home. The lamp gateway (also called bridge or connection hub) might be:

1. A separate box with own separate mains power supply.
2. Built into one lamp that can take care of communication to a group of lamps
3. Built into every lamp
4. Not necessary in case the user interface and the lamps are communicating by the same protocol e.g. WiFi

The protocol for communication between the lamps might e.g. be by Z-wave, Zigbee, 6LoWPAN, WiFi or Bluetooth.

Standby consumption

The SSL Annex has compiled some test data on smart lamp products and tested in Annex Member Country lighting laboratories:

- 11 models purchased in the USA by Erik Page & Associates and tested at ITL Boulder,
- 3 models purchased in Europe and tested by the Swedish Energy Agency, and
- 2 models purchased and tested by the Australian government.
- 3 models purchased in Denmark and tested by DTU Photonic.

Some of the models in the different countries are the same. The sample sizes for these models tested are small (1-3 units) therefore the test results should at this stage only be interpreted as indicative measurements.

Tests on this limited number of smart wireless LED lamps have revealed that the standby consumption for the different models varies between 0.17 and 2.71 W with most smart lamps having a standby consumption in the interval 0.4 - 0.6 W.

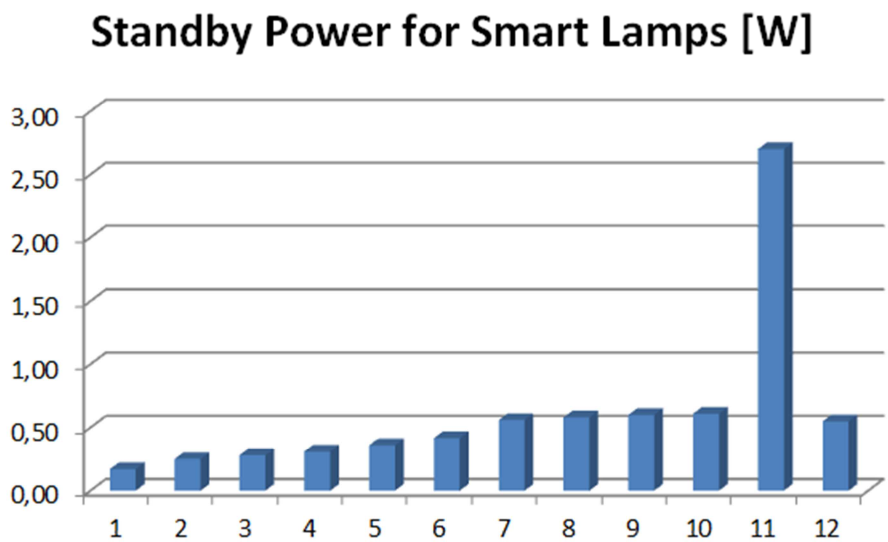

Figure 2 Standby consumption for smart lamps

The lamp with a much larger standby consumption than the others includes a built in lamp gateway in every lamp. Some of the other models have separate lamps gateways. The average standby consumption for these separate gateways is 1.5 W.

In the home, most lamps are used 1-2 hours/days [ref. 2]. The figure below shows the yearly consumption for the lamp models providing 225 – 1000 lm. When the operation time is 1 hour per day five of the lamps consume more than half of their annual energy consumption in standby mode. When the operation time is increased to 2 hours per day only two of the lamps use half of the consumption in standby mode – anyway in this case the standby consumption is still considerable for 8 of the 9 lamp models.

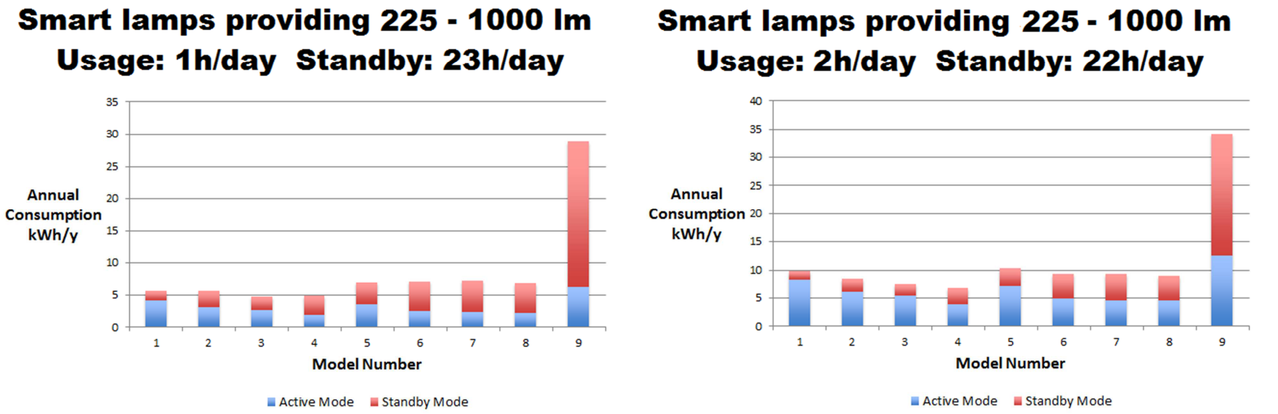

Figure 3 Annual consumption for smart lamp providing 225 – 1000 lm

The high standby consumption described above is similar to experience with standby consumption for other products where manufacturers first focused on the new features before turning their attention to reducing the standby power consumption. For example the load for smart phones chargers has for some models now been reduced to as little as 0.05 W.

Efficacy for the active mode and the total real total Efficacy

The total energy consumption for the tested smart lamp models is much higher than for simple LED lamps of equivalent light output operated by the normal on/off switch. When the standby energy consumption is taken into consideration the efficacy is lower. The real efficacy for the smart lamps is calculated as shown below.

$$\textbf{Real Efficacy} = \frac{(Luminous\ flux \times ON\ time)}{\{(ON\ power \times ON\ time) + (STANDBY\ power \times STANDBY\ time)\}}$$

Below the efficacy only for the active mode is compared with the real efficacy.

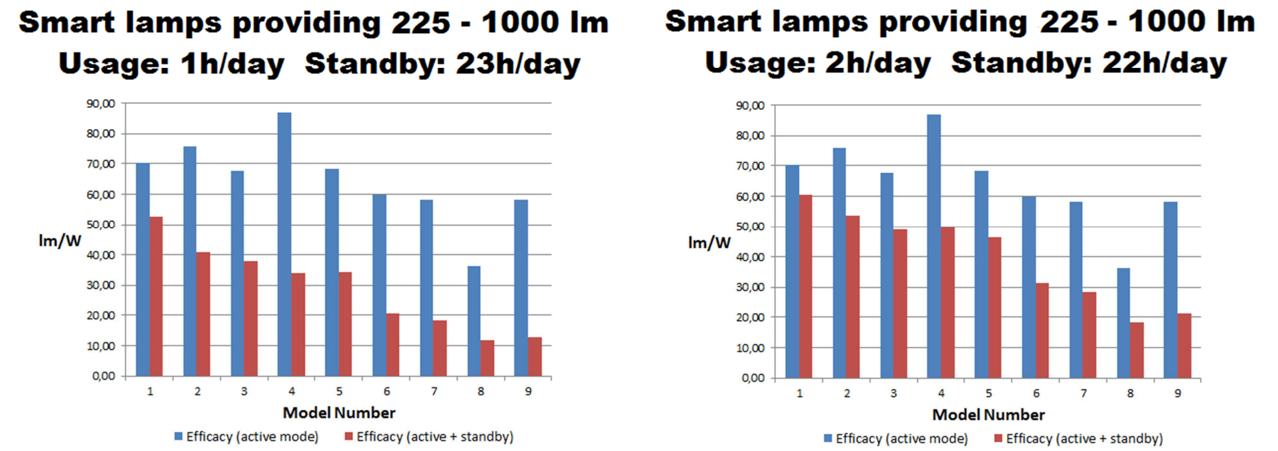

Figure 4 Active mode efficacy and real efficacy for smart lamps providing 225 – 1000 lm

For the 9 lamp models, the active ‘ON’ efficacy varies within the interval 36 – 87 lm/W. With an operation time of 1 hour per day, the real efficacy varies within the interval 12 – 53 lm/W. For two lamps, the real efficacy is down at the level of incandescent lamps. In case of an operation time of 2 hours per day, the real efficacy varies within the interval 18 – 61 lm/W.

Decoration lamps

Smart lamps with low lumen output also appear at the market. These lamps are mainly for decoration. They have low energy consumption but there could be many of them. For these lamps, the measurements show that that the standby consumption constitute a larger share of the total consumption than for the smart lamps with higher lumen output.

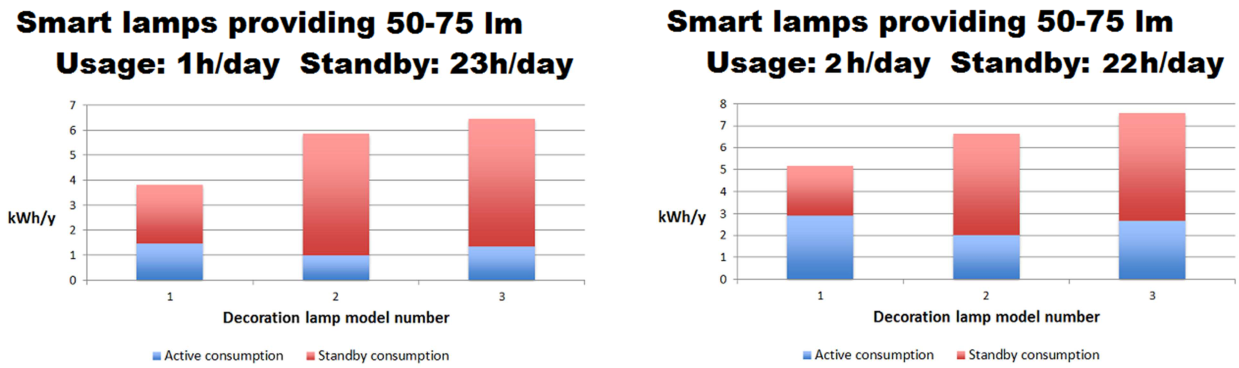

Figure 5 Annual consumption for smart lamp providing 50 – 75 lm

For the decoration lamps, both the ON efficacy and the real efficacy are very poor. The real efficacy is less than half of the efficacy for incandescent lamps.

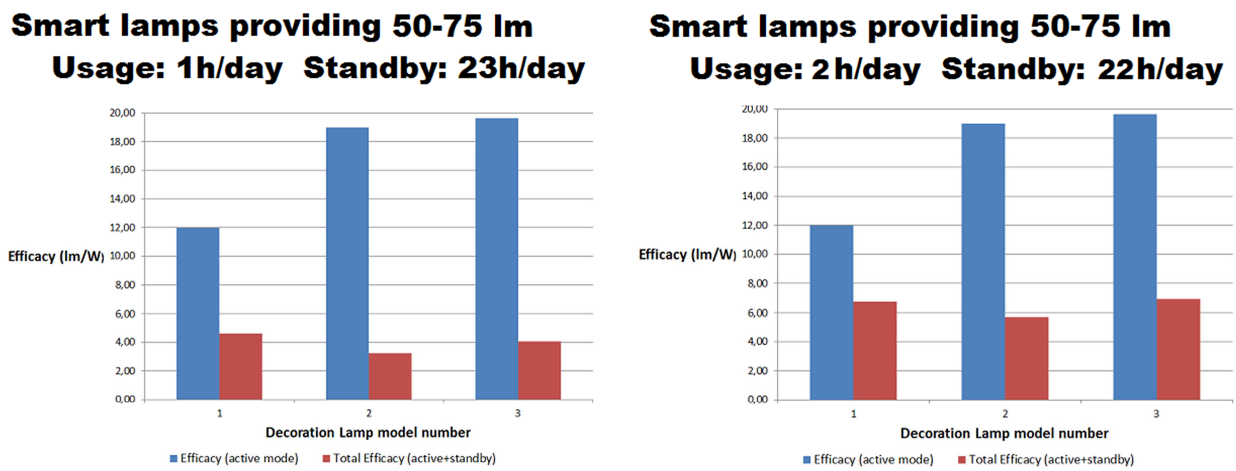

Figure 6 Active mode efficacy and real efficacy for smart lamps providing 50 – 75 lm

Need for metric for measurements and test of functionality

The colour tunability has huge influence on the lumen output, the power consumption and thus the efficacy. Measurements at one of the most common smart lamp providing 600 lm, shows the efficacy is 13 lm/W in case the lamp is tuned to give blue light, 43 lm/W for red light, 110 lm/W for green light, 75 lm/W for warm white and 88 lm/W for cool white.

This complexity shows there is a need for standards for how to measure the performance for smart lamps. As it might take time before a standard is available for smart lamps, the SSL annex intend to develop a metric for smart lamp measurements as an interim methodology that can be used temporary.

It seems also to a challenge to explain the consumers about the smartness of these lamps and the influence on their energy consumption.

The challenge for regulation

The energy impact of smart lamps is difficult to predict as it is dependent on the functionality developed and the mode of deployment by the suppliers, as well as the user acceptance and usage of the functionality. Everything equal, the first measurements indicate smart lighting might increase the lighting energy consumption considerably as seen for other technologies and functions that involves network standby. Even with a small standby wattage, this might significantly increase the annual energy consumption.

It seems thus desirable to regulate the standby consumption for smart lamps at an early stage to provide an envelope of consumption under which the functionality may be developed, but on the other hand this should not inhibit the potential for innovation.

At present there appears to be no definition that adequately encapsulates the potential functionality, nor the network standby modes of these smart lamps, and consequently no suitable test methodology against which to regulate. This clearly presents a challenge for the regulator.

A 'wait and see' strategy before attempting to develop suitable test methods and regulation is with high risk as the technology may be rapidly embedded as soon as the actual high prices start to decrease. Hence, development of an interim test methodology and associated regulation may be considered appropriate. For the voluntary US EnergyStar set of requirements has lately been discussed if it could be appropriate to require the standby power is below 0.5 W. In the ongoing revision of the EU lighting regulation which will come into effect within some years, the Danish Energy Agency has proposed to consider a requirement of maximum 0.3 W.

Summary

Smart lamps combine technology breakthroughs in wireless communications and light emitting diodes (LEDs). The lamps are typically controlled by a smartphone app that enable that the lamps can dim, change colour, shift to new scenes or programmed lighting changes over time. All this are provided simply by touching your phone. However, the lamps consume energy even when they are not in use.

The first indicative measurements show the standby functions drastically increase the lamp’s total energy use and the standby energy can be larger than the energy used for providing lighting. In order to better understand smart lighting features and their associated energy use, the IEA 4E SSL Annex has launched a new study on the energy performance of smart wireless lighting. Examination of the lamps as well as the communication protocols and gateways are expected to provide an evidence base for making recommendations to the governments.

In the future, there might be dozens of wirelessly controlled lamps in a single home, which taken together could result in high standby power losses. Therefore, the IEA 4E SSL Annex hopes that their study already now will help to raise attention to the standby usage, so that design improvements can be made to the circuits leading to lower smart lighting standby power. Some lamps already operate with 0.17–0.25W standby power while most lamps use more than the double of this and in one case the standby consumption is ten times higher. So design improvements for smart lamps are certainly possible in order also to become energy smart.

References

[1] The SSL Annex works internationally to support efforts at a national and regional level by addressing the main challenges with SSL technologies in order to develop a consensus on harmonised approaches to SSL performance and quality. The work of the SSL Annex spans a wide range of initiatives including guidance for policy makers, quality and performance tiers and support for laboratory accreditation, see http://ssl.iea-4e.org/. The SSL Annex is collaborating with the IEA EDNA (Electronic Devices and Networks) Annex which focuses on all kind of network connected devices including smart lamps, see: http://edna.iea-4e.org/about.

[2] Assessment of the initial situation in the participating countries, PremiumLight, IEE/11/941/SI2.615944, Energy piano, 2013

Large-Area Solid State Intelligent Efficient Luminaires

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Abstract

Light emitting diode (LED) technology for lighting applications has experienced a tremendous increase in performance and price erosion in the recent years and is expected to dominate the lighting market within few years from now. In addition to impressive efficiency values and its impact on energy savings, LED technology has brought about new research areas namely Human Centric and Smart Lighting. LEDs have also opened the door for new design concepts. In particular, LED-based, large-area thin luminaires for e.g. office lighting is a market worth millions and is receiving a considerable amount of R&D efforts. Although already available commercially, most LED-based large-area luminaires today do not fulfill the claimed specifications putting at risk a deep market penetration of LEDs for this type of products. We believe that improvements on the system design as well as added intelligence will greatly support LED-based luminaires to surpass even the most stringent requirements and allow further energy savings. Here, we introduce a lighting system which comprises a flexible LED-based light source, an innovative light management solution and integrated intelligence for color and luminance tuning. All the technological packages are currently being developed in the Framework of the EU-funded R&D project, LASSIE-FP7. Here, we provide the first results obtained on the light management system. Optical simulations and preliminary experimental results indicate the potential of this solution for efficient, large-area, low-cost modules with excellent light quality.

Introduction

The International Energy Agency (IEA) estimates that lighting represents almost 20% of global electricity consumption [1], similar to the amount of electricity generated by nuclear power and equivalent to 70% of the emissions from the world's light passenger vehicles. Hence, the development and implementation of more efficient lighting systems will undoubtedly make a significant contribution to controlling global CO_2 emissions. In addition, LEDs do not contain Mercury, in contrast to high efficiency fluorescent lamps.

Commercially available white LEDs have crossed the 150lm/W barrier and 300lm/W has already been demonstrated [2]. Such high efficacy values together with standard lifetime values in excess of 50'000 hours under continuous operation, makes LEDs the most convenient light source for energy savings. In fact, LED technology is expected to conquer the lighting market in the coming years with a penetration rate of 56% by 2016 [3].

On the other hand, soon after the beginning of this century, a new type of photoreceptors (ipRGCs; intrinsically photosensitive retinal ganglion cells), were discovered which control many biological functions, including the circadian rhythm [4][5]. This discovery triggered a new discipline in lighting, the so-called *Human Centric Lighting (HCL),* which sets lighting at the core of those external stimuli that affect human performance and well-being. Ever since the discovery of ipRGCs, a considerable amount of experimental evidence has been collected that confirmed the strong link between luminous excitation (spatial and angular distribution of the light intensity and primarily its spectral distribution), and visual acuity, mood alteration, sleep quality and productivity to mention some examples. Contrary to conventional incandescent or fluorescent light sources where the spectral light distribution is fixed, a plethora of different spectra are possible with LEDs allowing improvements in human health and well-being.

LED technology, as a digital-ready light source, is naturally compatible with electronic switching circuitry integrated in the driving electronics. This so-called *Intelligent or Smart Lighting* represents the

shift of lighting from its most basic mandate to a much more valuable and useful asset, including HCL and energy savings far beyond what is attainable with non-intelligent lighting systems.
For example, the first generation of intelligent lighting products will include relatively simple smartness such as occupancy and daylight sensing as well as CCT/luminance tuning. In addition, controls can be integrated that respond to pre-loaded user preferences.
This will likely be follow by a second generation with more advanced intelligence including more sophisticated add-ons whose implementation will be only possible with SSL [6].

White emitting LEDs

White LED emission can be achieved using the so-called *multichannel or RGB approach.* This approach uses a combination of red, green and blue LEDs (often 4 or 5 different "colors" are used). When appropriately driven, such combination produces a white light of a predetermined correlated temperature (CCT). Although compatible with CCT tuning, it suffers from low efficacy values at medium to low CCT values due to the low efficacy of green/amber LEDs in the so-called *green gap*. In addition, the spectral distribution of the resulting white light, formed by the superposition of few relatively narrow spectra, results in a substantial number of missing wavelengths and the consequent color misinterpretation, (poor color rendition) of objects with emittances around these wavelengths. Finally, the differential aging of the red, green and blue LEDs must be properly compensated to avoid undesired CCT shift during device operation.

Alternatively, in the so-called *phosphor approach*, a layer of a yellow phosphor-containing resin is deposited on top of a blue LED chip. Part of the blue light passing through the phosphor layer experiences Stokes down-conversion resulting in a white emission whose CCT is determined by the composition of the phosphor layer and its thickness.

Phosphor-containing white LEDs give a much broader emission spectrum than CCT-equivalent RGB LEDs and hence better color rendition. In fact, CRI values as high as 98 have been reported using a combination of green, yellow and red phosphors [7][8]. Moreover, with phosphors near to 100% quantum yields, phosphor white LEDs are also more efficient than RGB.

However, the phosphor approach also suffers from CCT shift and efficiency drop related to the wavelength shift of the pumping blue LEDs during operation and more importantly, to the phosphor degradation and emission quenching observed primarily at high temperatures. For example, a 10% drop in down-conversion quantum efficiency or in the phosphor absorption coefficient (in the blue region) can cause a color shift close to a MacAdam ellipse step size 4 [9]. High temperatures also cause local delamination of the phosphor layer form the LED surface which results in a noticeable CCT shift [10]. These temperature-driven detrimental effects can be highly alleviated by locating the phosphor layer away from the emitting chip in what is known as *remote phosphor approach.*
One of the main drawbacks of the phosphor approach is that although the phosphor content and layer thickness can be adjusted for any desired CCT, this cannot be dynamically tuned for a given phosphor layer.

Here we propose a technology based on the joint use of the multichannel and remote phosphor approaches. *Color changing foils (CCF)* manufactured by BASF (Ludwigshafen, Germany) are used for down-conversion. BASF CCFs are flexible thin foils with embedded organic phosphors. Due to the existence of unresolved molecular vibrational levels, light emission is broader from organic phosphors than from inorganic. Thanks to the synergetic effect of the selected combination, broad spectral emission and associated high color rendition as well as dynamic CCT and/or luminance tuning are possible together with high efficacy, long lifetime and acceptably low cost.

Large-area SSL

Large-area light sources comprising a collection of individual LEDs spatially distributed represent the most convenient option when large amounts of light are needed. They are widely used in a variety of lighting segments including office, shop-retail, hospitality, industrial and architectural which are predicted to worth 40 billion Euros in 2020 [11].

OLED, the organic counterparts of LEDs are flat, thin, areal emitting devices that have been seen as the "next big thing" in large-area lighting and the natural successors of LEDs for large-area products. However, several factors exist that are causing OLEDs to struggle in their way to the general lighting market and that, according to many, will likely prevent this to ever happen.

On one hand, OLED technology lags well behind LED in terms of efficacy, lifetime, lumen output and lumen-per-dollar. Indeed, the ever promised large-area, low-cost, solution-based R2R fabrication on flexible substrates is not even close to become a reality in the next years. On the contrary, commercially available OLEDs today are expensive, glass-based devices, manufactured using several expensive evaporation processes under vacuum in a sheet-to-sheet process and with emissive areas of typically 100cm^2 or less (see Table 1).

Table 1. Performance comparison of current best commercially available OLEDs and standard LED-based large-area lighting module [1]

	Highest Lum. flux OLED	**Largest Area OLED**	**Highest Efficacy OLED**	**Large-Area LED Module**
Model	**Philips FL300**	**LG N6SD30**	**LG N8SA30**	**LG Innotek ReflectA Free**
Area (mm^2)	102 x 102	320 x 320	100 x 100	600x600
Thickness (mm)	3.0 [1]	1.0[8]	1.97[12]	69.5
Luminous flux (lm)	300 [2]	850[9]	75	3'000
Efficacy (lm/W)	>50 [3]	60	80	97
CCT (K)	3'000 [4]	3'000	3'000	3'500
CRI	>80	>90	>80	80
LT70 (10^3 hours)	10 [5] 50 [6]	40 [10, 11]	50[13]	~50[16]
Cost (lm / $)	2.2 5 [7]	1.25[15]	0.91 [14]	25.4[17]

Another important aspect, that is generally overlooked, is the detrimental impact that temperature has on OLED device lifetime. Although OLEDs operate under relatively low temperatures (because the light is generated on the whole emissive area), they are considerably more sensitive to small temperature changes than LEDs. For example, increasing the operating temperature from 45^{o}C to the moderate value of 65^{o}C can reduce the lifetime by as much as two times as shown in Figure 1 [12].

On the other hand, non-transparent, scattering out-coupling films used to boost device efficacy and to alleviate cavity-related angular color shift, are not compatible with appealing mirror-like or transparent off-state appearance, a many-times cited advantage of OLED technology.

Finally, most of the mentioned unique selling points of OLED technology such as large-area, low-cost, transparency and flexibility are continuously been eroded by LED-based technology.

Indeed, although LEDs are intense point-like light sources (a mid-power, 1mm^2 phosphor white LED can easily deliver luminance levels higher than 50Mio nits compared to ~5'000 for the brightest 100mm^2 OLEDs; Phillips Brite FL300) there are solutions to engineer them into large-area (flexible and/or transparent possible) luminaires.

[1] Please note: *[1] Including thermal backplate, housing and wiring; [2] At 340mA and 19V; [3] at 300 lumen ; [4] 4000K planned; [5] at 300 lumen; [6] at 125 lumen; [7] [f]or orders above 40 OLEDs (http://www.oled-info.com/philips-launches-new-sales-campaign-sees-oleds-reaching-mass-market-early-2017); [8] bare OLED9; [9] 1700mA; 8.5V; [10] at 3'000 cd/m^2; [11] using LG proprietary "Face Seal" technology; [12] with housing and wiring; [13] initial luminance not specified; [14] https://www.maritex.com.pl/en/oled-lg-chem-lighting/olp-n8sa30-i-34063-c-33634; [15] http://www.oled-info.com/lg-details-price-their-320x320-mm-and-truly-flexible-oled-lighting-panels; [16] not quoted for the lamp, given figure is based on the lifetime information of the LED chips; [17] http://www.futurelightingsolutions.com/en/Technologies/Semiconductors/Lighting-Solutions/LED-Light-Modules/Pages/3029132-LLFML66-38K308A.aspx?ManufacturerName=LG-INNOTEK&isFLS=true&IM=0*

$$LT_{70}(L,T,n,m) = LT_{70}(L_0,T_0) \times \left(\frac{L_0}{L}\right)^n \times \left(\frac{T_0}{T}\right)^m$$

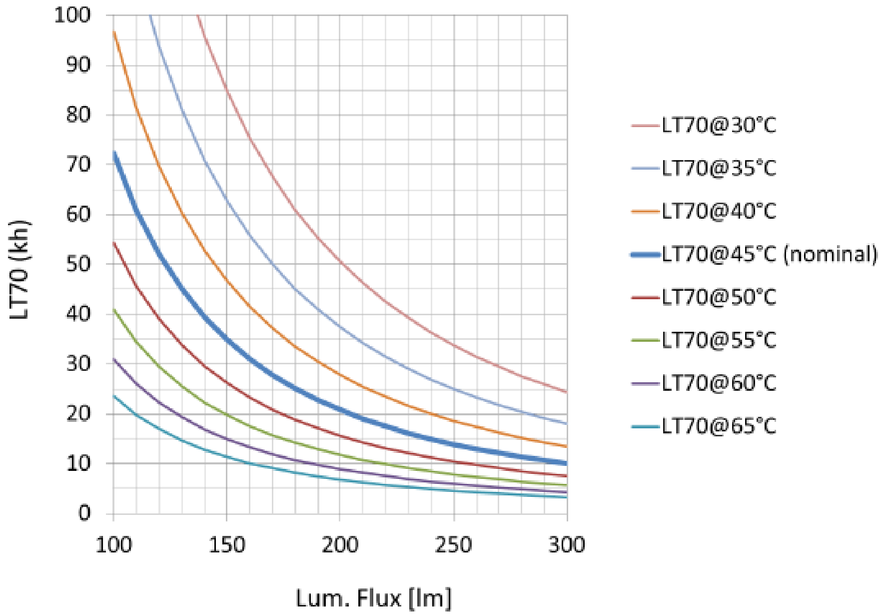

Figure 1 OLED device lifetime as a function of initial luminance and temperature [12].

A common approach is to "hide" the LEDs behind a diffusing plate. In spite of its simplicity, large-area spatially uniform luminance completely free of appreciable hot-spots requires a distance of few centimeters between the LEDs and the diffuser, an approach incompatible with thin form-factors and /or device flexibility. Although diffusers with large hiding factors can be used in closer proximity to the sources, it comes at a substantial drop in efficacy as shown in Figure 2 Optical transmittance versus half power angle (hiding power) for diffusing plates based on volumetric scattering manufactured by Bayer. Modified from [18].

A way to overcome this issue is the so-called *edge-lit technology* where the LEDs are distributed across at least one of the edges of a thin transparent plate. The light emitted by the LEDs is coupled inside the waveguide and guided through total internal reflection (TIR). Light extraction features replicated on the emissive surface/s of the waveguide disturb the TIR and allow the guided light to escape.

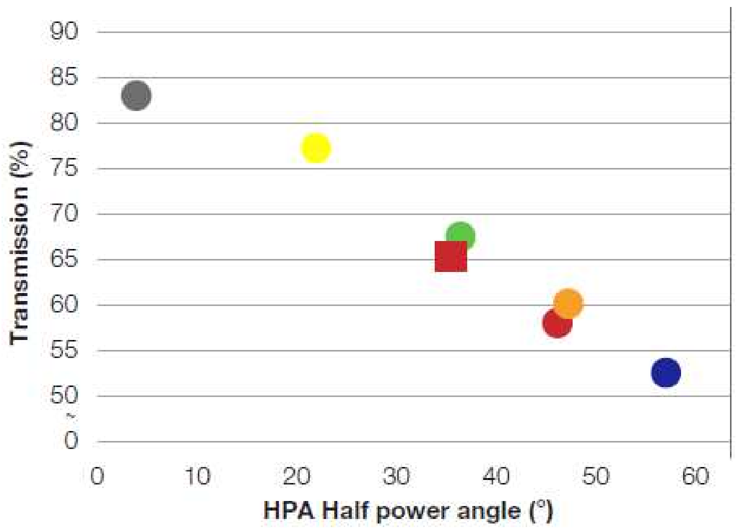

Figure 2 Optical transmittance versus half power angle (hiding power) for diffusing plates based on volumetric scattering manufactured by Bayer. Modified from [18].

In large-area edge-lit luminaires, large part of the emitted light has to be guided across long distances which results in high optical losses even when relatively transparent materials such as e.g. PMMA are used (PMMA absorption coefficient of 0.0017 mm^{-1} [13] leads to 17% optical losses on a 100mm length). In addition, since the waveguide perimeter increases only as the square root of its area, high LED densities are required as the emissive area increases which demand efficient thermal management solutions to avoid excessive heat at the waveguide edges to prevent associated detrimental effects such as waveguide deformation and/or material yellowing.

A different approach consists in embedding white LEDs inside the waveguide, evenly distributed across its area [14]. This technology solves some, but not all the issues related to edge-lit. For example, moderate-to-high temperatures around the LEDs over sufficiently long time periods may degrade the waveguide material locally close to the LEDs. Therefore, unless an expensive, short-pitch LED configuration is adopted, the maximum attainable brightness of the luminaire is noticeably limited. Also, non-standard side-emitting LEDs or precisely tilted standard surface-emitting LEDs are required as otherwise most of the light will leave the waveguide without undergoing TIR, giving rise to appreciable hot-spots. Moreover, as the LEDs must be fully embedded into the waveguide, a minimum thickness of the latter is mandatory. Finally, access to the LEDs in e.g. the event of LED failure seems rather complicated if at all possible.

Our light management technology (Patent pending) was designed and engineered to overcome the mentioned shortcomings. By using diffractive nanostructures, light emitted around the normal to the LED surface can be efficiently in-coupled even for standard, surface-emitting, LEDs located outside the waveguide. The spatial separation of light emission and light guiding/out-coupling results in a minimum temperature-driven degradation effects in the waveguide material and allows the use of much thinner waveguides.

Transparent diffusers for large-area LED-based lighting

Here we describe in detail the lighting module that was outlined in the previous sections. A sketch of the optical system cross-section (limited to only one LED, i.e. the system *Unit Cell*) is given in Figure 3.

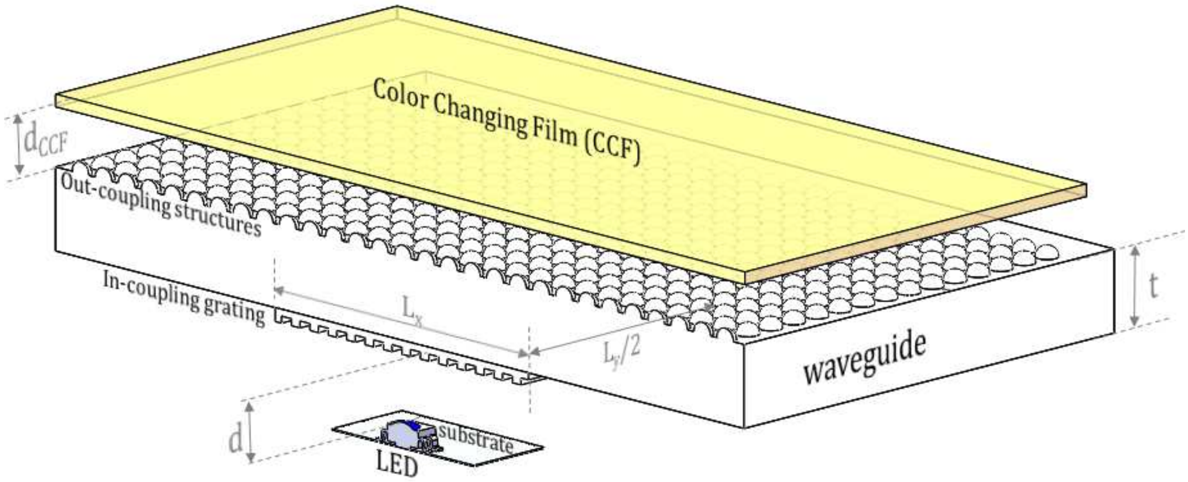

Figure 3 Schematic cross-section of the light source and waveguide with replicated in-coupling diffractive grating and out-coupling microstructures on the opposite surface of the waveguide as well as the color conversion film (CCF).

The system comprises a series of blue LEDs bonded onto a flexible, R2R compatible film following a highly spatial regular pattern. LED films with highly optical reflectance or transmittance respectively must be used for single or double surface emission lighting modules. Heat management structures are fabricated onto the foil surface/s in order to dissipate the heat generated by the light sources [15]. Several hundreds of microns above the LED foil, a thin (<1mm thickness) transparent (e.g. Polycarbonate, PMMA, etc.) foil serves as the optical waveguide. Diffractive optical nanostructures (gratings) concentric to the LEDs replicated on its bottom surface are responsible for light in-coupling into the waveguide whereas replicated micro and/or nanostructures on its top surface allow light escaping to the free space in a relatively well-controlled manner.

In-coupling efficiency: System optimization

In order to achieve a thin form-factor efficient R2R compatible system, its geometry must be optimized. The interplay between waveguide thickness, *t* and its distance to the LED substrate, d_{LED} as well as the grating dimensions, L_x and L_y, determines the overall performance of the system.

For example, the use of very thin waveguides or too large gratings results in *back out-coupling* since, due to optical reciprocity, any in-coupled ray hitting the grating from inside the waveguide after TIR at its top surface will be partially out-coupled back to the LEDs substrate (see Figure 4) resulting in optical losses and reduced control on the light distribution in the system. In particular, the maximum thickness, *t*, is given (in one dimension) by:

$$t = \frac{L_x/2}{2\tan\theta}, \qquad \textbf{Equation1}$$

where θ (~42^o depending on the refractive index of the waveguide material) corresponds to the critical angle for TIR (see Figure 4).

On the other hand, since R2R manufacturing is pursued, a maximum waveguide thickness exists, dictated by the required flexibility for R2R processing.

Finally, the maximum possible light collection (amount of LED light that is collected by the grating) is required for maximum amount of in-coupled light. Light collection for a given d_{LED} increases with increasing L_x and L_y.

These magnitudes were optimized using ray-tracing optical simulations. The calculated percentage of the emitted power by the LED (OSRAM Topled Compact blue) that reaches the corresponding grating is shown in Figure 5 as a function of the grating area, for different d_{LED} *values*.

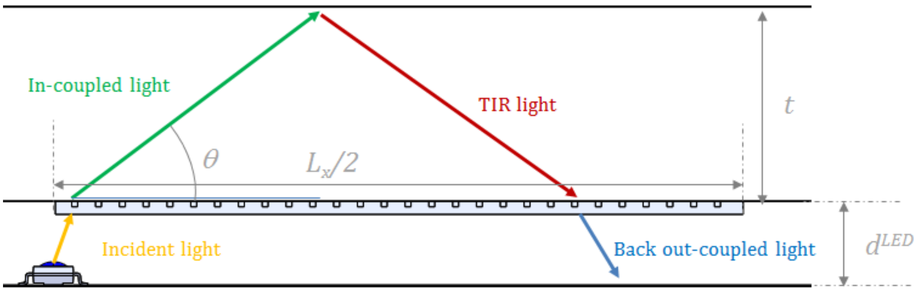

Figure 4 Schematic cross section of the light management system (CCF not shown) showing the relevant geometrical parameters. Back out-coupling (blue line) is expected when the in-coupling gratings extends beyond the second TIR.

A decent amount light collection can be achieved using gratings with areas similar to the LED emitting surface located at a distance *A* above the LED emitting surface. According to Equation1, for waveguides with submillimeter thicknesses, back out-coupling is prevented; a value compatible with 2R2 processing.

It is well known that grating diffraction efficiency depends substantially, for a given set of grating parameters, on the angle of incidence. On the other hand, since the value of d_{LED} is comparable to the geometrical dimensions of the LED emitting chip (0.6x0.9mm for OSRAM Topled Compact), the latter cannot be considered as a point source. As a result, different, non-trivial irradiance angular distributions are expected at different x, y coordinates of the gratings.

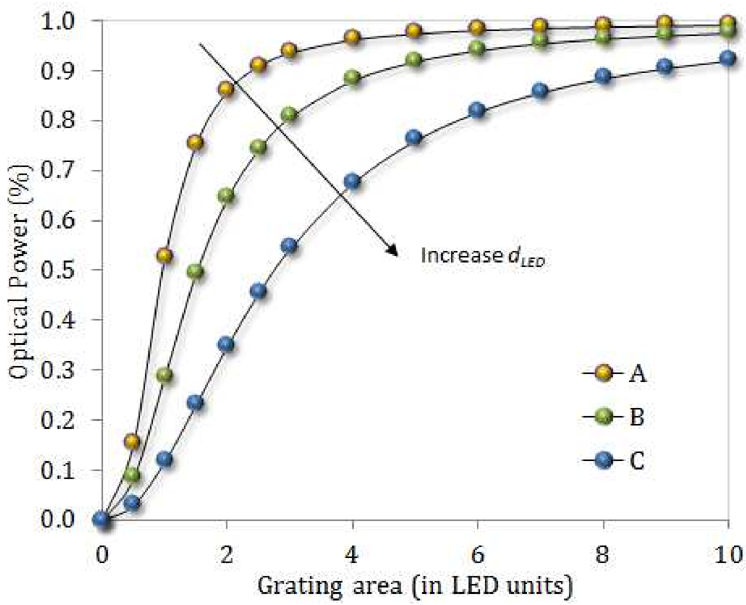

Figure 5 Calculated percentage of emitted power reaching the in-coupling grating as a function of the grating area and grating-LED distance, d_{LED}. The grating area is calculated in units of the area of the LED chip.

For this reason, in-coupling gratings with smoothly varying grating parameters across the x, y coordinates according to the irradiance angular distribution at these coordinates are expected to give the optimum performance. In order to keep ourselves manufacturing realistic, grating area was segmented into 5 concentric zones (see Figure 6). The geometrical dimensions of each of the five segments were selected so that each segment receives 25% of the optical power incident over the complete grating. The angular distribution of the incident light calculated using again ray-tracing optics and the real angular emission spectrum emission of the LED provided by the LED supplier. The results for incident angles in the XZ and YZ planes are shown in Figure 7.

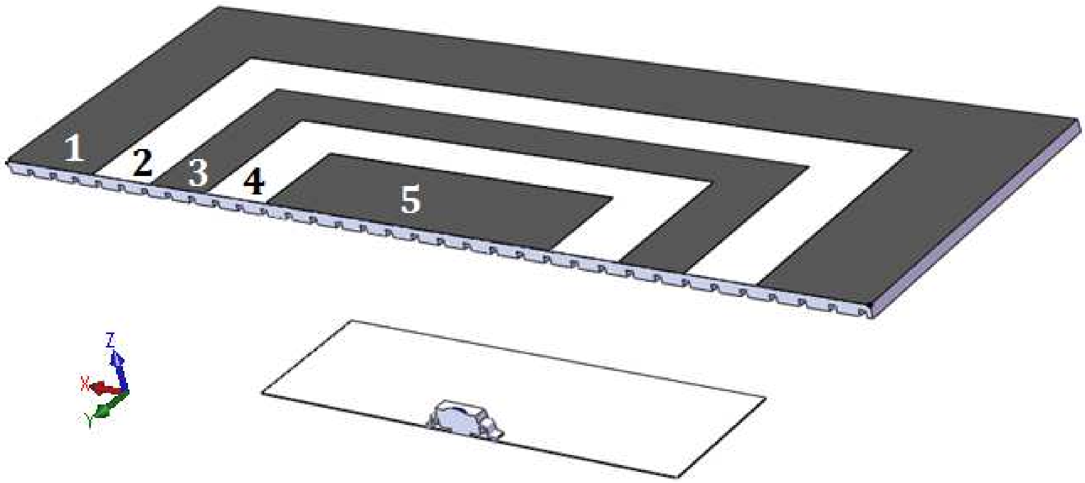

Figure 6 Sketched cross-section of the segmented in-coupling grating showing the 5 segments with respect to the LED source.

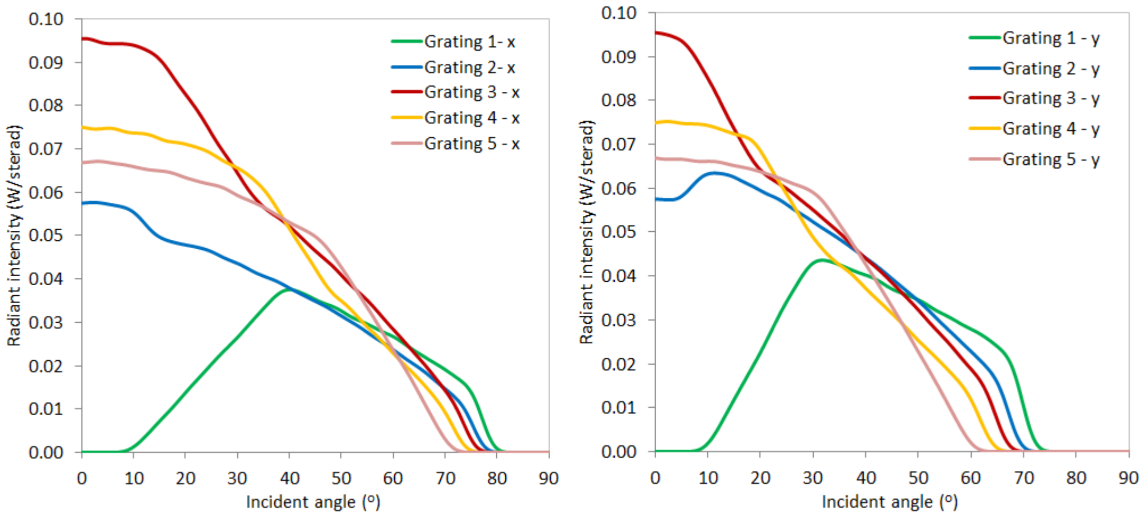

Figure 7 Angular distribution of the irradiance as a function of incident angle in the XZ (left) and YZ (right) planes on the five zones of the grating for the selected LED (Topled Compact from OSRAM) and selected geometrical parameters (d_{LED}=0.25mm; L_x= 1.4mm; L_y=0.9mm).

Rigorous Coupled Wave Analysis (RCWA) simulation software coupled to an optimization algorithm was used to optimize the grating parameters of the 5 segments for maximum light in-coupling. Well-known manufacturability limits and the previously calculated irradiance patterns were used as boundary conditions and light input respectively.

The in-coupling efficiency as a function of polar and azimuthal incident angles for gratings with optimized parameters is shown in Figure 8. In-coupling efficiency values over 80% can be achieved for a wide range of azimuthal incident angles and polar angles close to the grating normal. For the real Lambert-type LED emission, a 54% in-coupling efficiency can be achieved. The remaining optical power is distributed almost equally into directly transmitted and reflected light.

The light reflection can be greatly recovered by using (as mentioned above) highly reflecting substrates. Flexible films with diffuse reflectance values well over 90% are currently commercially available from different manufacturers (3M, BrightView, Bayer, FusionOptix, etc.)

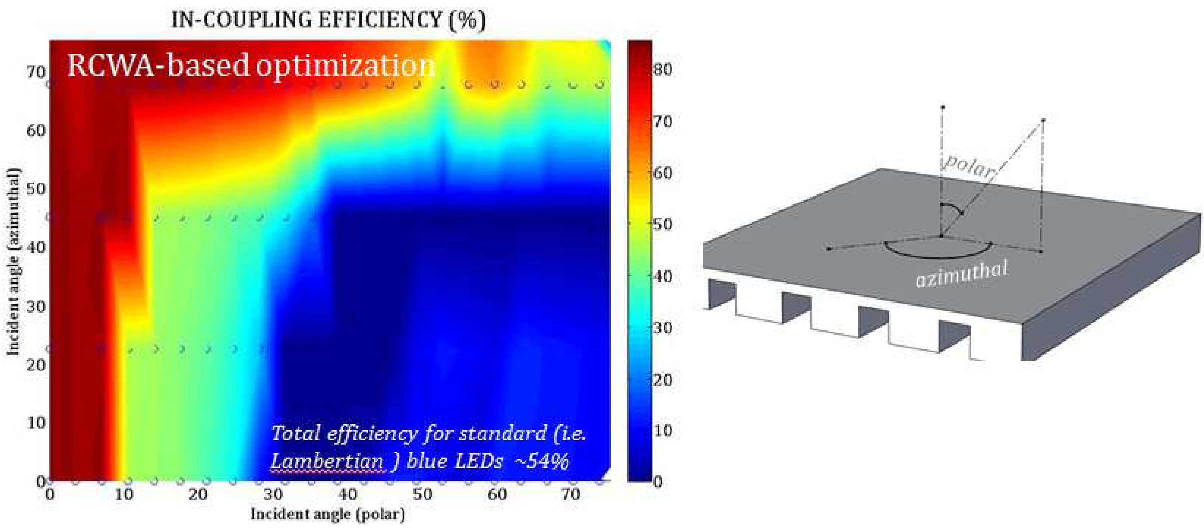

Figure 8 Left) Calculated in-coupling efficiency as a function of polar and azimuthal incident angles. Right) Definition of polar and azimuthal angles with respect to the grating orientation.

The spatial distribution of the electromagnetic field just after the first air/waveguide interface given as a by-product of the optimization process can easily be converted into a collection of k-vectors or geometrical rays. Such a collection of rays can be used as the light source in ray-tracing optics to track the transmitted light and the propagation of the in-coupled light through the waveguide. As a result, light out-coupling structures can be optimized according to the real distribution of light inside the waveguide. The outcome of such optimization will be published elsewhere.

Fabrication and initial results

In-coupling gratings, with the optimum parameters were hot-embossed on a 0.5mm thick, 50x50mm^2 area Polycarbonate (PC) foil. As mentioned above, the replication of the grating must be restricted to areas comparable to that of the emitting LED chip (see Figure 5).

Moreover, in order to better spatially distribute the light inside the PC foil, two grating orientations where replicated, perpendicularly oriented with respect to each other as shown in Figure 9 and Figure 10. In particular, each grating pixel contains a large collection of 0.1x0.1mm^2 subpixels with their grating oriented perpendicularly with respect to each other.

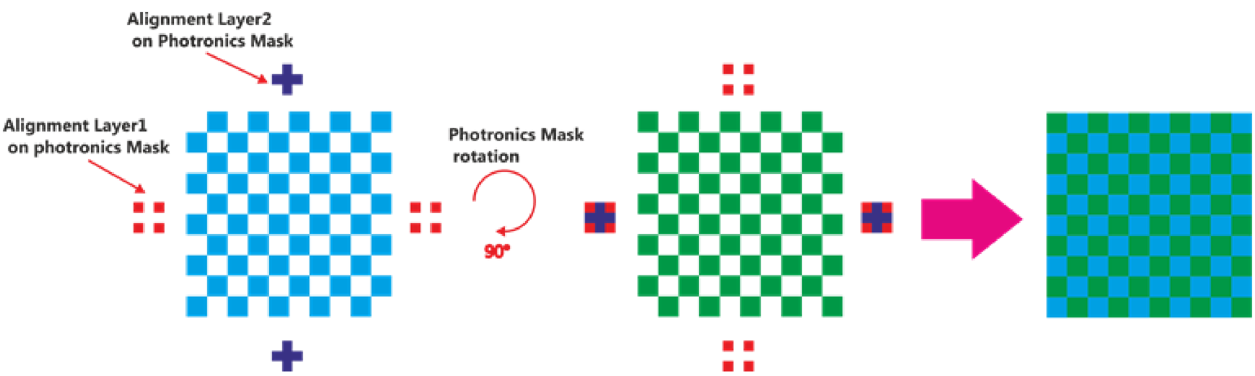

Figure 9 Schematic view of the process for the replication of perpendicularly oriented in-coupling gratings.

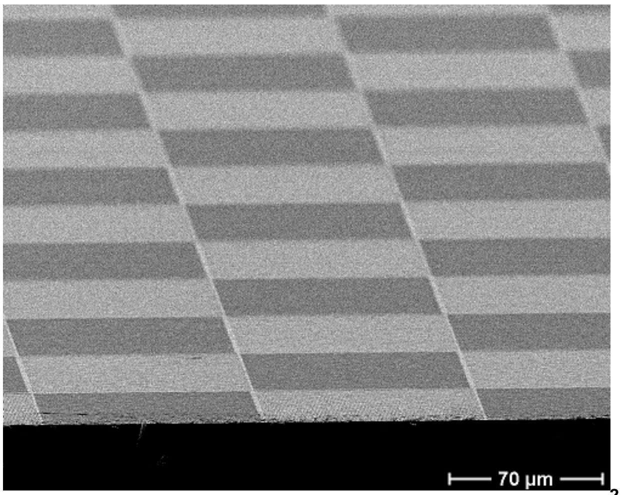

Figure 10 SEM picture of the pixelated gratings showing the 0.1x0.1mm^2 grating pixels with the grating grooves perpendicularly oriented with respect to one another.

The in-coupling capabilities of the fabricated foil can be readily seen in Figure 11. The fabricated foil was illuminated with a 3x3 array of blue LEDs (λ=455nm). Considerable light in-coupling is observed only when the grating pixels are well aligned with the LEDs (Figure 11 right).

It must be noted that a relatively efficient in-coupling was observed in two perpendicular directions. Light guiding (and subsequent out-coupling) at relatively long distances from the light source can be achieved by the use of out-coupling films.

We believe that the proposed diffractive transparent diffusers can be provided highly uniform light emission over large area even in combination with long-pitch LED arrays. Thin-film, flexible color converting foils (see below) will finally allow the fabrication of flexible thin homogeneous efficient lighting modules.

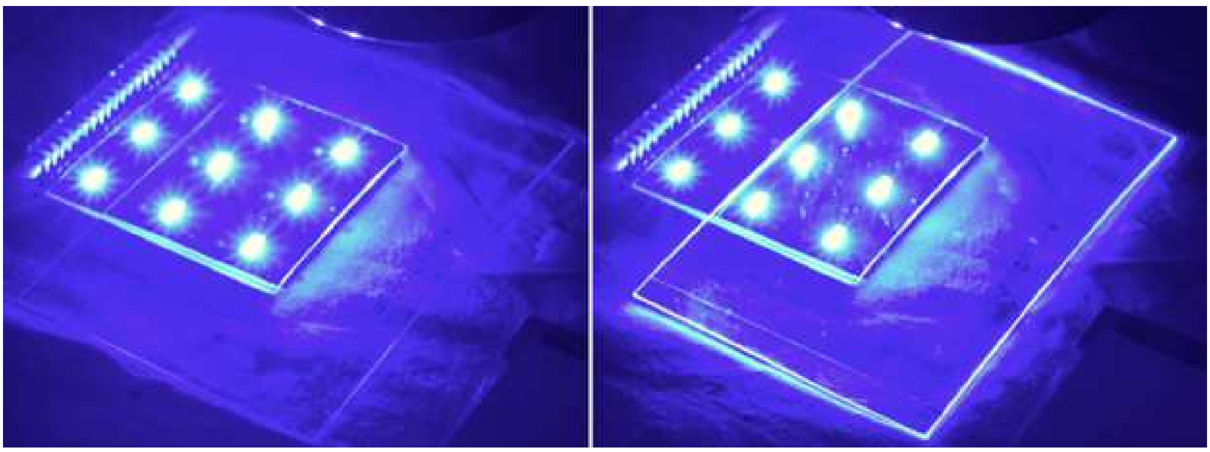

Figure 11 3x3 array of pixelated in-coupling gratings replicated on a 0.5mm thick PC foil located on top of a 9x9 array of blue LEDs (OSRAM Topled Compact). Left) No light in-coupling observed due to the misalignment of the gratings and the LEDs. Right) Edge emission of the light in-coupled by the well-aligned gratings.

Color changing flexible foils (CCF) for large-area SSL

Flexible phosphor-containing foils manufactured by BASF (Ludwigshafen, Germany) can be used to convert the blue LED light into high-quality white light. BASF CCFs contain organic phosphors and scattering particles extruded together into thin polymer foils such as e.g. PET, PMMA, PC, etc.
The composition and thickness of the foil was adjusted to give 3'500K CCT when pumped with a 450nm blue LED (such as OSRAM Topled Compact). For the initial assessment, the CCF was

laminated on a transparent (50x50mm^2) blue LED foil and the integrated emission characteristics of the system measured in an integrated sphere set-up. The CIE coordinates of the blue and the white (blue + CCF) foils are presented in Figure 12 CIE coordinates of the blue and white (LED + CCF) LED foils measured in an integrating sphere set-up at REGENT LIGHTING (Basel, Switzerland). The Planckian locus represented by the thick black line. The white point lies perfectly on the Planckian locus at a CCT of 3'546K, in excellent agreement with the target value. Moreover, CRI and CRI9 values of 94 and 78 were calculated from the measured integrated emission spectrum. Finally, a relatively high efficacy above 100lm/W was measured considering that the system was not optimized for efficient light recycling.

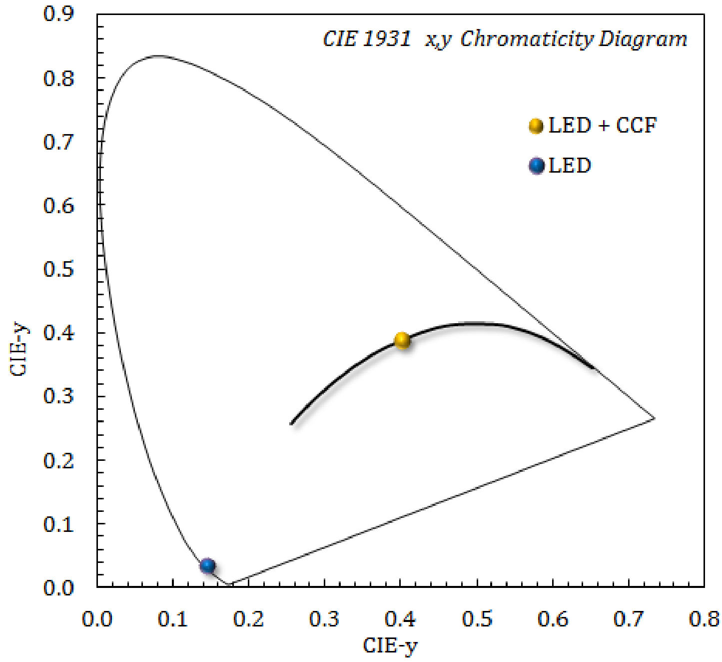

Figure 12 CIE coordinates of the blue and white (LED + CCF) LED foils measured in an integrating sphere set-up at REGENT LIGHTING (Basel, Switzerland). The Planckian locus represented by the thick black line.

Table 2 Integrated emission characteristics of the blue and white (LED + CCF) as measured in an integrated sphere set-up at REGENT LIGHTING.

Integrated Characteristics	Luminous flux (lm)	Efficacy (lm/W)	CIE-x	CIE-y	CCT (K)	CRI	CRI9
LED	-	26	0.1468	0.0336	-	-	-
LED + CCF	128 [2]	103	0.4020	0.3876	3546	94	78

Conclusions

A new approach has been presented for the fabrication of thin-film efficient LED-based lighting modules compatible with R2R production. This approach overcomes the fundamental limitations of current technologies for thin-film lighting modules and allows the fabrication of highly efficient, thin SSL lighting modules with high luminance uniformity and light and excellent spectral properties through proper engineering of the diffractive transparent diffusers and color converting foils, even with long-pitch LED arrays.

[2] Please note this corresponds to 512 lumen for a 10x10cm^2 area; much higher than e.g. best OLED today; Philips Brite FL300.

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Does energy efficient lighting result in lower energy use? The evidence from a near zero energy housing development

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Abstract

Lighting technologies have witnessed remarkable improvements in energy efficiency over the past few decades with the developments in compact fluorescent and light emitting diode technologies. But has the application of energy efficient lighting delivered a lower energy use outcome? This paper compares the domestic lighting energy use of a number of comprehensively monitored houses within two Australian housing developments constructed a decade apart. The Mawson Lakes estate was built in the early 2000's, whilst the Lochiel Park estate was designed to be nearly zero energy and was constructed in 2009-2015. Whilst the lighting technology applied at Mawson Lakes was more typical of standard construction practice at that time, strict urban design guidelines and encumbrances were sanctioned in Lochiel Park to reduce the energy used for lighting as well as other major energy services including thermal comfort and water heating.

The application of energy efficient lighting technologies at Lochiel Park has resulted in significant energy savings. Analysis of the monitored house energy data within each estate shows that the near zero energy houses use, on average, 40% less energy for lighting than those in the nearby Mawson Lakes estate. In addition, there was a reduction of average peak power drawn by the low energy housing lighting circuits of 61%. This is despite the wiring convention used in Australia which combines the ceiling and wall-mounted light fittings together with other devices such as ceiling fans and bathroom exhaust fans and heat lamps which are more prevalent at Lochiel Park. The case studies indicate that the application of energy efficient lighting technologies, in the context of contemporary lifestyles, reduces both energy end-use and peak energy loads.

Keywords: energy monitoring, domestic lighting, low energy houses, installed capacity, lighting power profile, peak demand

Introduction

The provision of energy services such as lighting, thermal comfort, food refrigeration and water heating in buildings is a major contributor to anthropogenic greenhouse gas emissions, and energy efficiency programs are at the heart of mitigation strategies for many nations [1].

Energy end-use studies in various countries has found that lighting is a significant energy end-use, which typically contributes around 5~16% of total household energy use [2-6]. Lighting demand as an energy service has been growing for several centuries, particularly as the provision of light has become more convenient, readily available, and affordable [7]. Although other studies suggest total lighting energy use may have started falling in regions which have adopted energy efficient technologies [8].

Policies

In the context of global action to address anthropogenic climate change, reducing energy demand from households has been, and remains, an important policy action [9, 10]. To date a wide range of lighting policy actions have been undertaken including the mandatory labelling of lamp efficiency, the introduction of minimum appliance efficiency standards such as the phase-out of incandescent globes, the provision of free compact fluorescent lamps (CFL) to hasten consumer transition, and the inclusion of lighting performance standards in building energy codes and standards.

In Australia, the national government introduced a phase-out of inefficient bulbs as part of a program to curb anthropogenic greenhouse gas emissions [11]; the phase-out affects the sale of lighting products with an efficiency level of less than 15 lumens per watt. In parallel the Building Code of Australia (BCA), part of the National Construction Code, introduced mandatory residential lighting requirements, which require the aggregate lamp power density of fixed lighting to not exceed 5, 4 or 3 W/m^2 for indoor, outdoor or garage lighting, respectively [12].

Technological developments

Technology change is also driving the tendency towards improved lighting efficiency. For example, the design flexibility of the light emitting diode (LED), its operational efficiency and appreciably longer effective life provide motivations away from alternative lamps. And like most mass produced consumer products, the relative cost of LED lamps is expected to fall over time as the technology matures and the market transitions.

But studies have shown that energy impacts are not just related to the efficiency of technologies, finding that energy use is also related to the demographic characteristics of building users and their lifestyle [13, 14]. From an end-user perspective, the relatively higher up-front cost of low energy lamps, the light output quality, and the convenience issues of product availability and compatibility with existing fittings, all impact the transition to low energy lighting [15, 16].

Given the various policy landscape, technology and behavioural related impacts, this study addresses the research question: does the application of energy efficient lighting deliver lower energy use outcomes? Utilising detailed energy use monitoring from two case study estates: one more typical of houses in the early 2000s, and the other a near zero energy estate; this comparison provides a strong indication of whether the application of energy efficient lighting technologies and contemporary household behaviour will deliver a lower energy use outcome.

Literature review

The past few centuries have seen significant domestic lighting technology change from candles to gas lamps to kerosene lamps to various forms of electric lighting from incandescent lamps to fluorescent tubes to dichroic halogen lamps to LEDs. Each has provided different light qualities, environmental externalities, and consumer benefits. Examining the more contemporary lighting technologies from an efficiency perspective, LEDs deliver equivalent lux levels for one fifth the energy of incandescent or halogen lamps, and one half the energy of compact fluorescent lamps [17]. Theoretically control systems can further reduce the amount of energy wasted lighting spaces that are not occupied or already have sufficient natural light. But these savings are viewed from an engineering calculation perspective before taking into account the behaviour of building users.

In observing the coal consumption of 19th century steam engines, Jevons [18] argued that improvements in engine energy efficiency increased the use of coal by making the technology more economically attractive, rather than delivering energy savings. This concept was taken up by Khazzoom [19] and Brookes [20] who postulated that economy-wide rebound effects, being the sum of direct and indirect effects, will absorb expected benefits and may lead to a net growth in energy use and greenhouse gas emissions. In simple terms, the theory argues that the more efficient a process becomes the more the end-users will consume the service, and for lighting this means that as lighting has become more convenient and cost effective, the greater the total energy impact.

The relationship between artificial lighting and human productivity has meant that the Jevons paradox has been demonstrated across the history of lighting technology change [7, 21]. Tsao et al. [7] examined lighting energy use across three centuries found that improvements in the efficiency facilitated lower lighting costs, greater access to lighting, greater per capita consumption of lighting, improvements in human productivity and associated increases in economy-wide energy use. Tsao et al. [7] point out that the historic rebound trend may not continue in all situations as indoor light levels near saturation (satisfies human need for light) and the price elasticity of demand closes to zero. Fouquet and Pearson [21] tracked income and price elasticity of demand for lighting over the past two centuries in the UK and found that rebound reduced as incomes grew, with rebound greater than 100 per cent during the nineteenth century, but reducing well below 100% during the twentieth century.

Detailed metering of developed world households in the 21st century supports this position of lower elasticity, for example a study in Sweden found lighting efficiency gains were delivered with only small levels of rebound [22]. Similarly, a German study of households found that the switch from incandescent or halogen lamps to CFL or LED technology will result in a rebound of around 6%, which suggests that significant energy savings are possible due to technology change [23].

The literature also contains substantial evidence that lighting design strategies that facilitate daylighting and encourage the use of energy efficient lighting and associated control systems can significantly reduce energy end-use for commercial buildings [24]. But as lighting is a relatively larger energy end-use in commercial buildings when compared to residential buildings, and less likely to be influenced on a daily basis by building users, this finding is not readily transferable to housing.

And although there have been many post-occupancy studies for low carbon and near zero energy homes [25-31], the energy end-use disaggregation has typically not separated lighting performance. Clearly there is a gap in the literature describing the actual performance of energy efficient lighting in low energy and near zero energy homes.

Lighting is used during periods of peak energy demand and therefore improvements in the energy efficiency of lighting may result in peak demand reductions. In heating dominated climates, winter peak loads are influenced by seasonal heating and lighting demand [6]. The Building Research Establishment [6] report noted that at least 20% of the winter electrical peak was attributable to lighting. Less is understood about the potential for lighting energy efficiency to reduce summer peak energy demand in cooling dominated climates.

The following case studies address these gaps in the literature by quantifying total energy savings and peak load reductions due to the application of energy efficiency lighting technologies in warm temperate climate near zero energy homes.

Methodology

Case Study: Mawson Lakes and Lochiel Park

The case study locations of Mawson Lakes and Lochiel Park, both in Adelaide (South Australia), are chosen because the first represents relatively typical local construction for the period 2000-2010, and the second represents atypical construction, being a near zero energy housing estate (constructed between 2009-2014). The contrast between the two estates is stark with Lochiel Park homes featuring the atypical application of passive design strategies, energy efficient technologies and equipment, and renewable energy technologies (e.g. solar water heating and photovoltaic systems). Further details of the Mawson Lakes homes is available at [32], and details of the Lochiel Park homes is available at [33].

Comparisons between estates, particularly across different time periods, is notoriously difficult because of the myriad of factors impacting energy consumption including local climate, household behaviour, socio-economic situation, and changes in lifestyles. In the case of the chosen case study estates, there is a noticeable difference in floor area with Lochiel Park houses having approximately 21% more conditioned floor area and approximately 30% more habitable floor area (see Figure 1). To address this issue the relevant analysis is normalised by floor area.

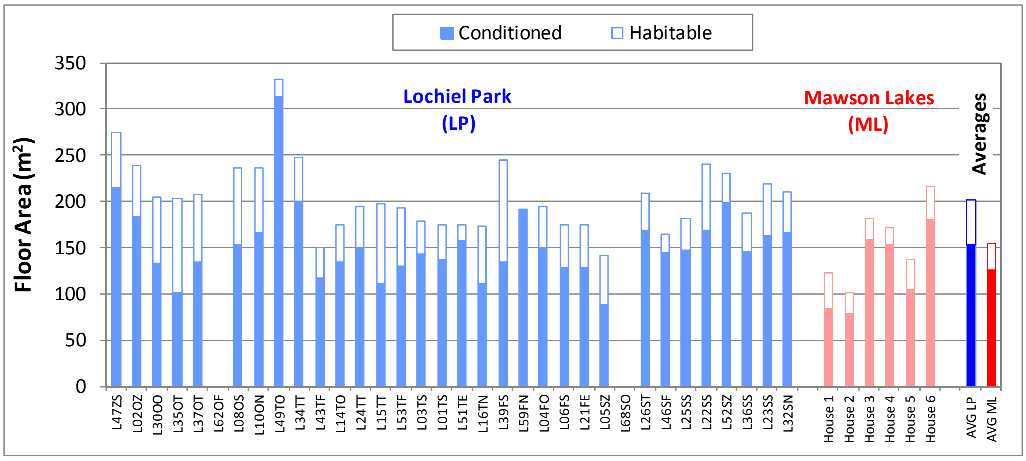


Figure 1: Habitable and conditioned floor area of the individual and average monitored Lochiel Park and Mawson Lakes houses.

Lighting data

The lighting technology and performance information utilised in this study comes from three main sources: (a) surveys of occupants; (b) appliance and equipment audits (house inspections) conducted by the authors; and (c) monitored energy end-use data.

Surveys regarding energy conservation attitudes and behaviours were administered to all Mawson Lakes residents to develop a greenhouse gas emission reduction scoresheet [32]. The results of surveys give some insight into the installed appliances and equipment.

Appliance audits were carried out in 45 Lochiel Park houses to gain an understanding of the types of energy using appliances and equipment used in modern low-energy houses. In addition to collecting the nameplate information of many major appliances, details regarding the number, type and power rating of plug-load and lighting devices were collected.

Overview of energy end-use monitoring systems

Mawson Lakes

Electricity and gas utilities monitored networks of houses within Mawson Lakes, where 50 and 140 houses had their electricity and gas monitored, respectively. Network data was made available to the authors of the scoresheet report [32]. Within these networks, six houses were monitored in detail, with disaggregation across heating and cooling, lighting, ovens, dishwashers and refrigerators. The lighting energy data was recorded in 15 minute intervals at increments of 6Wh, using a current transformer and a data logger; giving an average power resolution of 24W.

Lochiel Park

Each house in Lochiel Park is fitted with an ‘EcoVision’ brand monitoring system, which includes an in-home feedback display, a programmable logic controller (PLC), and a variety of intelligent meters and sensors [34, 35]. Each monitoring system records and displays the residents’ real-time water, electricity and gas usage. Lighting energy data presented in this study is collected from a sub-set of 10 houses with disaggregation to major appliances (e.g. ovens, refrigerator, dishwasher, heating and cooling, water heating) and electrical circuits (e.g. lighting circuits).

The raw electrical energy consumption data is collected remotely each month, which is recorded at minute intervals using wattmeters with resolution of 1.25, 1 and 0.5Wh. This translates into average minute power consumptions of 75, 60 and 30W, respectively. This data is converted to 15 minute average blocks to match that of the Mawson Lakes data to facilitate a fair comparison of lighting circuit power profiles. This does not affect the energy consumption over the monitoring period, and has only a minimal smoothing effect on the average power profile, as shown in Figure 2.

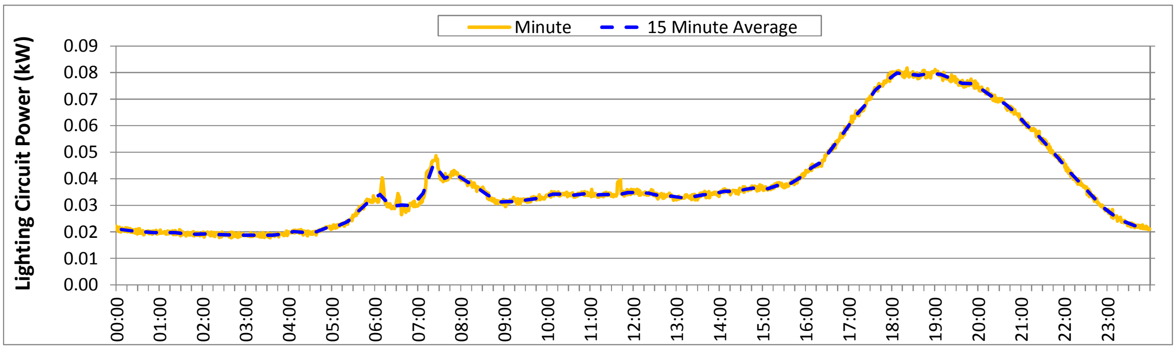
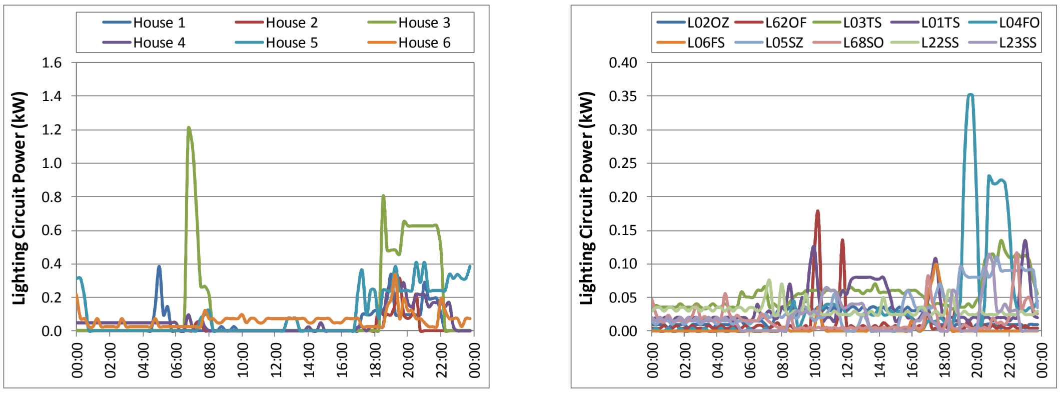


Figure 2: Effect of converting the average Lochiel Park minute (by minute) lighting data to 15 minute averages.

Note that both housing estates are wired to the same specification which allows ceiling and bathroom exhaust fans, as well as bathroom heat lamps, to be wired on lighting circuits. Due to limitations with monitoring equipment (i.e. the resolution of wattmeters and coarse equivalent powers), it is difficult to disaggregate lighting power from that of ceiling fans, exhaust fans or heat lamps. In addition, luminous flux was not measured and hence neither the lighting levels nor efficacy is presented here.

The Mawson Lakes lighting data, presented in this study, was monitored between April 2002 and March 2003, whilst that from Lochiel Park was monitored between January and December 2014. An example of a single day lighting circuit power profile, for both estates, is shown in Figure 3.



(a) Mawson Lakes (31-03-2003) **(b) Lochiel Park (31-12-2014)**

Figure 3: 15 minute lighting circuit power profiles of monitored house within both estates.

Lighting technology and circuit details

Mawson Lakes

Although no appliance audits were performed nor were records kept of the number or types of lighting technologies used within Mawson Lakes homes, the surveys indicate that 47.2% of respondents believed they were using energy-saving lighting - the author's believe halogen dichroic low-voltage down lights, typically installed in new homes at that time, were deemed by respondents to be energy-efficient in the survey, and this may hence be misleading given modern energy-efficient lighting technologies. The surveys also showed that 81.9% of respondents did not have ceiling fans installed and of those that did, the mean was 2.8 fans per household [32], likely installed in bedrooms. This, in addition to the fact that these houses were constructed well before the phase out of inefficient light bulbs, justifies the authors assumptions that the majority of lights used are incandescent and or halogen down lights and that very few ceiling fans are included on these lighting circuits.

Lochiel Park

The lighting systems installed at Lochiel Park predominantly use compact fluorescent lamps (CFL), with a smattering of light emitting diodes (LED) usually on stairwells, and linear fluorescent lights mostly used in the carport or garage. The appliance and equipment survey found that Lochiel Park homes on average have 41 fixed internal lights, 6 portable lights and 10 outdoor lights. A breakdown of the quantity and installed capacity of fixed, portable and outdoor/shed lights for each individual household is shown in Figure 4. Lochiel Park houses were required to have ceiling fans fitted to each living space and bedroom.

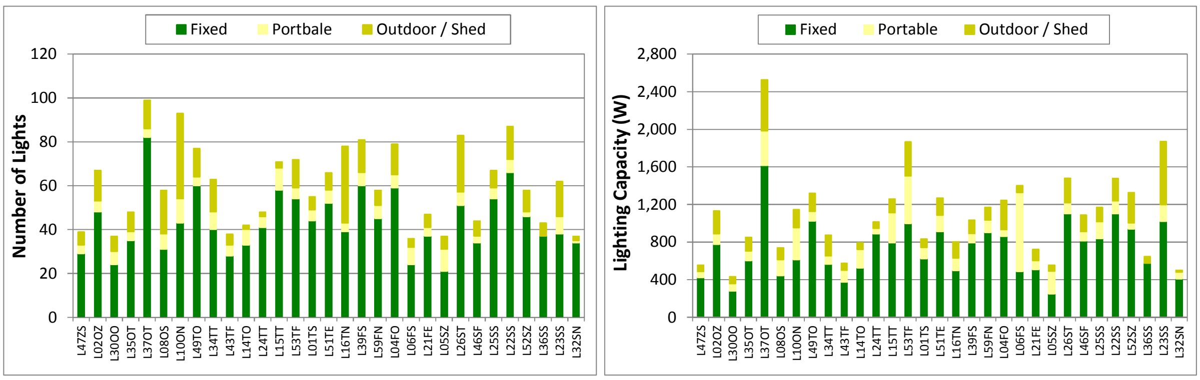


Figure 4: Quantity (left) and installed capacity (right) of lights in audited Lochiel Park houses.

The appliance audit and survey also revealed that the fixed indoor lighting capacity ranges from 247W to 1,613W; the average being 726W. This is shown as a function of habitable floor area in Figure 5a, together the subsequent BCA requirement for new houses (i.e. a density of 5W/m^2). Figure 5b shows the individual household indoor fixed lighting densities. The energy density ranges from 1.35 to 7.8, with a mean of 3.56, which is well below the current regulatory requirement. They also show that a small number of houses (i.e. 5 of 31) exceed the current energy density requirement, which is due to these houses being completed before this lighting requirement was mandated.

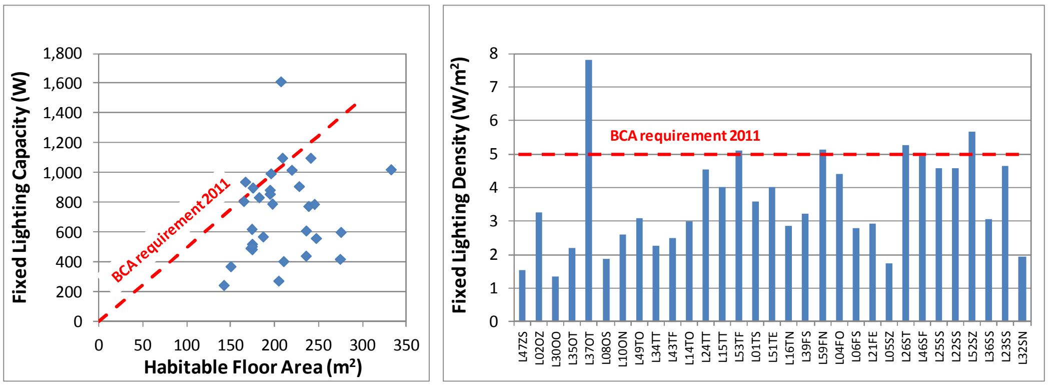


Figure 5: Fixed lighting (a) installed capacity vs. floor area, and (b) energy density, of the audited Lochiel Park houses. The dashed line represents the 2010 BCA requirement of 5W/m^2.

Do these monitored houses represent their respective estates?

Mawson Lakes

Given the relatively high completion rate, 60%, of the surveys administered within the Mawson Lakes households, it is assumed that the survey findings are be reasonably representative of the population at Mawson Lakes [32]. In addition, the average networked Mawson Lakes utility data was assumed to be representative of the entire estate. This network average closely matches that for the average of the six monitored houses for the majority of the year, with the exception of summer period, where the average electrical consumption of the sub-set is nearly 50% larger than the network average in some of the summer months. From the perspective of lighting energy use, the house sample is assumed to be sufficiently representative of the Mawson Lakes estate.

Lochiel Park

The sub-set of detailed monitored houses is representative of the Lochiel Park estate across a range of relevant factors, as shown in Figure 6 and Figure 7. The former shows the monthly estate wide average total electricity demand for the estate as a column with an error bar that represents one standard deviation of this; the point represents the monthly average of the 10 detailed houses. Similarly, Figure 7 shows the average household habitable floor area, installed fixed lighting capacity and energy density of these houses, along with the estate wide standard deviation (error bars) and the average of the 10 detailed monitored houses (points). These figures demonstrate that across the various house characteristics, the average of the 10 houses, where the lighting data is obtained, is relatively close to the average of the estate, and falls well within one standard deviation, giving confidence that the lighting data presented here is representative of the houses within the estate.

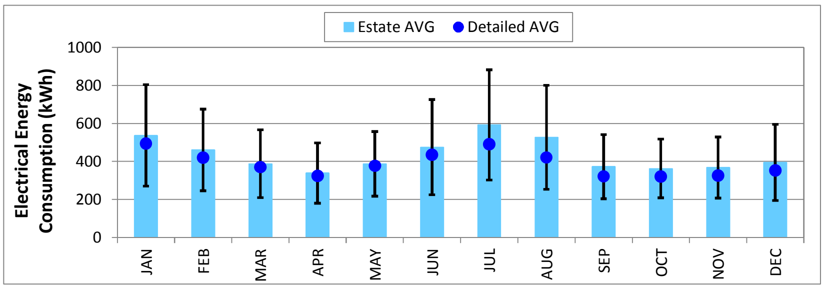


Figure 6: Average estate-wide and 10 detailed monitored house monthly electrical energy use.

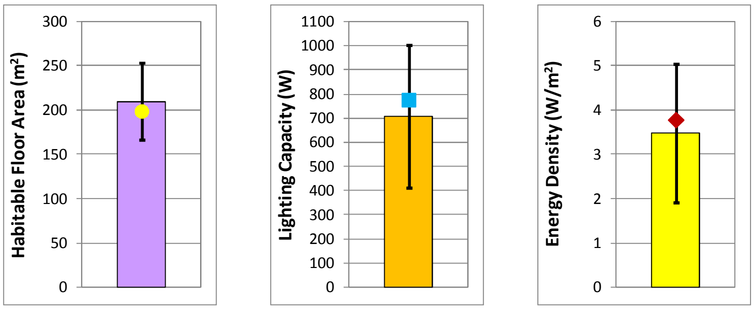


Figure 7: Average detailed monitored house (points) vs. average audited house (columns) floor area, installed fixed lighting capacity and indoor lighting density.

Lighting performance of monitored houses

Energy consumption

The annual electrical energy consumed by lighting circuits of the detailed monitored houses within both the Lochiel Park and Mawson Lakes housing developments, is shown in Figure 8. The figure shows that despite the wide variety in both estates, the average Lochiel Park house use 40% less lighting energy than the average Mawson Lakes house; 326.5 kWh to 547.5kWh. This is despite the Lochiel Park houses being 30% larger in size (habitable floor area), which suggests that the lighting technologies employed in these homes provide the service more efficiently than for Mawson Lakes.

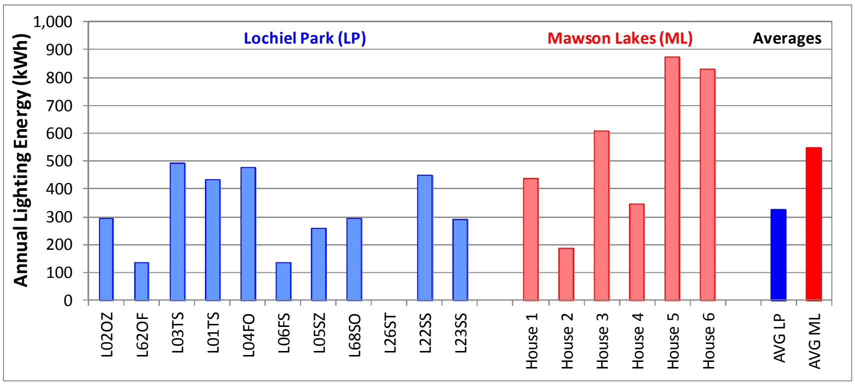


Figure 8: Individual and average annual lighting circuit energy per development.

Figure 9, which normalises the lighting energy by habitable floor area, verifies the significant improvement in performance and shows that on average the Lochiel Park houses use half of the lighting circuit energy per floor area than those of Mawson Lakes. Further research to confirm lighting use patterns for each estate is necessary to confirm the relative importance of efficiency to the end result.

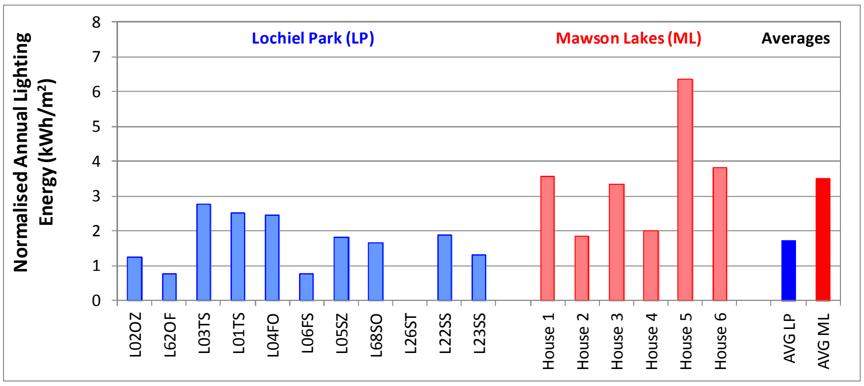


Figure 9: Individual and average normalised annual lighting circuit energy per development.

Although a significant reduction of lighting circuit energy has been demonstrated, it is difficult quantify how much of this is due to the use of efficient lighting technologies alone. Power profiles (signatures) of lighting and ceiling / bathroom exhaust fans are unknown and likely vary from appliance to appliance and house to house. It should be noted that the Lochiel Park houses have more ceiling fans per home, compared to those in Mawson Lakes, and therefore a larger portion of the total lighting circuit energy may be accounted for by fans. Also, the lighting energy reductions achieved in the Lochiel Park houses may be due to improved daylighting (i.e. house orientation, window placement, skylights), and this impact cannot be quantified without lighting power signatures patterns.

Comparison with other studies

Although international comparisons are difficult due to factors including climate, culture, building typology and socio-economic impacts, the following comparisons highlight significant differences in lighting energy end-use. A Norwegian research has found annual average energy use for lighting at around 1,050 kWh/year or around 8.8 kWh/m^2/year [36], representing the impact of available sunlight and local building typology. In the United Kingdom average energy use is much lower than Norway at around 508 kWh/year, or around 6.7 kWh/m^2/year [37]. In Australia, a country with more available sunlight, the figures for both Mawson Lakes and Lochiel Park (3.4 and 1.7 kWh/m^2) show an expected lower average lighting energy use per floor area, although the total average lighting energy use for Mawson Lakes is similar to that of the UK due to the larger average floor area.

Power profiles

Peak lighting circuit power demand

Figure 10 summarises the individual and estate average peak lighting circuit power demand (15 minute blocks) throughout the monitoring period, showing that the combination of energy efficient lighting technologies and daylighting strategies can on average reduce the peak lighting circuit power by 61%, from 1,080W to 412W. This is despite the higher penetration of ceiling fans in the Lochiel Park houses. It is not expected that the power demanded by bathroom exhaust fans and heat lamps should significantly vary between both housing estates.

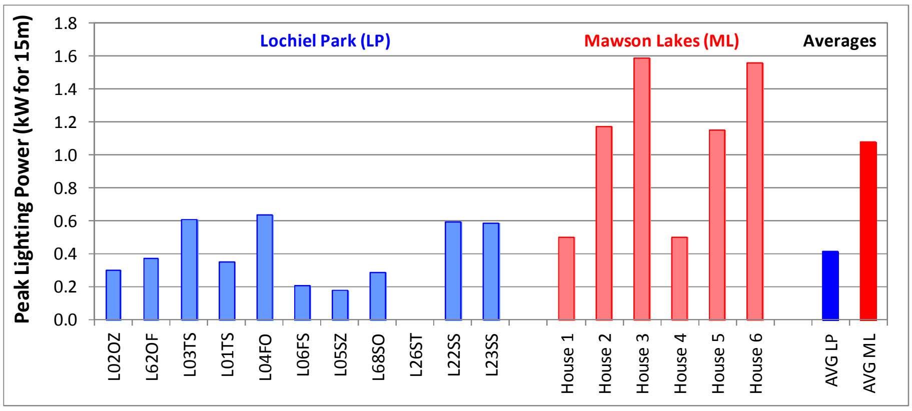


Figure 10: Individual and average peak lighting power drawn (15 minutes) per development.

Although the introduction of energy efficient lighting technologies has clearly significantly reduced the peak lighting circuit power, it is not clear what impact this has on total household peak power demand, and what the contribution of lighting circuits is on the peak demand of the monitored houses.

Lighting circuit contribution to peak power demand

Table 1 summaries the contribution of lighting circuit devices / appliances during peak power demand events throughout each respective monitoring periods. The information shows that peak events occur at different times of the day and on different days throughout the year, with about half of these occurring in both summer and winter; the exception is House 6 from Mawson Lakes whose peak demand occurs during Spring where the combined air conditioners and electric domestic water heater make up about 94% of the house's peak electrical demand. Overall, lighting devices do not significantly impact on the peak electrical demand of both sets of houses, and surprisingly there is one house in each data set (L06FS and House 3) that does not use their lighting circuit / appliances during their peak demand event. On average there is a clear reduction of the contribution between the developments, where the Lochiel Park houses contribute just over 1% to peak demand, whilst those in Mawson Lakes contribute to about 2.9%.

Figure 11 shows the average daily lighting circuit power demand of the monitored house for each estate in summer and winter, as these are the seasons in which peak electrical demand events occur. Each figure also shows the estate annual average daily profile as dashed lines. The profiles indicate a time difference of about one hour between the annual average peaks, as well as both the summer and winter peaks. The figures show a significant reduction in the peak for each season, with the average summer peak power demanded by the Lochiel Park lighting circuits reduced by 52.8% compared to Mawson Lakes, whilst those in winter and for the full year are reduced by 63.6% and 64.3%, respectively. The smaller reduction in summer could reflect the higher use of ceiling fans in Lochiel Park, and that reducing waste heat from inefficient lights may also reduce these cooling loads.

Table 1: Peak power demand events and contribution of lighting circuits on peak demand.

Estate	House	Peak Power (kW)	Date	Time	Lighting Power (kW) at peak	Contribution of Lighting at peak
Lochiel Park	L02OZ	4.290	16/01/2014	14:45	0.045	1.05%
	L62OF	5.920	16/01/2014	19:15	0.024	0.41%
	L03TS	6.987	02/02/2014	16:45	0.105	1.50%
	L01TS	9.279	14/07/2014	10:15	0.050	0.54%
	L04FO	6.413	07/02/2014	18:15	0.195	3.04%
	L06FS	4.377	11/08/2014	07:30	0.000	0.00%
	L05SZ	3.135	24/08/2014	11:00	0.023	0.74%
	L68SO	7.118	14/12/2014	00:00	0.132	1.85%
	L22SS	7.071	23/07/2014	16:30	0.025	0.35%
	L23SS	6.996	11/08/2014	21:45	0.045	0.64%
	AVG	**6.159**	N/A	N/A	N/A	**1.01%**
Mawson Lakes	House 1	7.560	20/01/2003	19:45	0.312	4.13%
	House 2	4.704	12/07/2002	17:45	0.192	4.08%
	House 3	10.608	22/12/2002	08:30	0.000	0.00%
	House 4	8.904	07/01/2003	17:15	0.024	0.27%
	House 5	8.208	30/07/2002	18:45	0.456	5.56%
	House 6	13.320	04/10/2002	23:45	0.456	3.42%
	AVG	**8.884**	N/A	N/A	N/A	**2.91%**

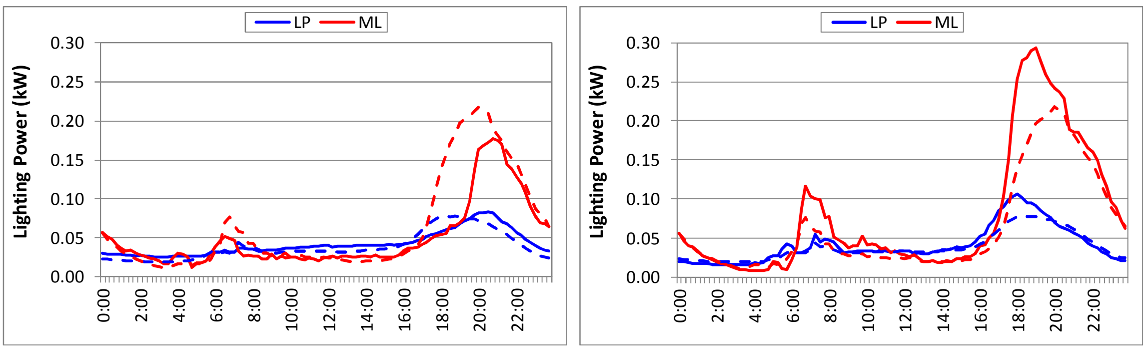


Figure 11: Average daily Lochiel Park (LP) and Mawson Lakes (ML) lighting circuit power profiles for (left) summer and (right) winter; the dashed lines represent the year-long daily average.

Conclusions

Lighting energy efficiency has been a key policy action in the context of addressing anthropogenic climate change. This paper has highlighted some of the numerous lighting policy changes worldwide and in Australia, with the policy goal of curbing residential greenhouse gas emissions.

Given questions raised in the literature about the likely rebound effect from improving the energy efficiency and therefore cost efficiency of providing lighting energy services, this study set out to determine whether the application of energy efficient lighting technologies in a residential setting would lead to a reduction in energy use. The comparison between the two nearby residential estates shows that the application of energy efficient lighting technologies combined with improved daylighting strategies significantly reduces the energy used for lighting energy services by about 40%. Further research to compare lighting use patterns for each estate is necessary to confirm the relative importance of efficiency to the end result.

Also noticeable was a significant reduction in peak power demand of the lighting circuits of about 61%, with benefits found across all seasons. And although the impact of lighting on total peak energy demand is relatively small, the related reduced internal heat load from improved lighting energy efficiency may also contribute to a lower summer cooling peak energy demand.

In light of the recent mandatory lighting performance requirements established by the Building Code of Australia, the installation and operation of energy efficient lighting technologies should result in a reduction in household energy use. The impressive energy savings presented here are magnified when normalised by floor area, as new houses are typically designed and built larger than ever before. The experience of Lochiel Park also shows that the mandatory building energy regulatory standards could be improved beyond the current $5W/m^2$ requirement for indoor lighting, leading to further total and peak energy demand savings.

Acknowledgments

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High Quality Super-Efficient Lighting Products: the SEAD Global Efficiency Medal

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Abstract

The Global Efficiency Medal competition, a cornerstone activity of the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative, is an awards programme that encourages the production and sale of super-efficient products. SEAD is a voluntary multinational government collaboration of the Clean Energy Ministerial. This competition recognises high-quality super-efficient products, enabling early adopters to identify the most efficient products and demonstrating levels of efficiency in commercially available and emerging technologies.

The fourth Global Efficiency Medal competition recognises super-efficient lighting products in four regions around the world. This competition complements existing labelling programmes and advances comparable and transparent international test methods that support market transformation programmes. For an emerging technology like LEDs, this competition enables manufacturers to distinguish themselves and informs policymakers about what is possible for this product group.

To establish the Efficient Lighting competition, experts and policymakers in participating regions provided input on lamps and luminaires that are either popular, high-volume products in each regional market or are niches for which inefficient products are currently used. Eight categories allowed manufacturers to nominate products in a range of sizes, colour temperatures, and lumen outputs.

In addition, to ensure the nominated products were of high quality and had the potential to influence the lighting market, the competition required nominated products to meet 19 quality criteria and to be sold below a cost threshold specified by product and region. These 20 criteria are part of an ongoing conversation about what makes a quality LED product that will satisfy consumer preferences for reasonable cost and high quality. The competition's criteria were based on similar requirements developed and published by the IEA 4E Solid State Lighting Annex.

Introduction: the SEAD Global Efficiency Medal competition

The fourth Global Efficiency Medal competition of the Super-efficient Equipment and Appliance Deployment (SEAD) Initiative recognises super-efficient lighting products in four regions around the world. The four regions were selected based on the governments participating in the SEAD Awards Working Group – Australia, Europe (based on participation from Sweden and the United Kingdom), India, and North America (with participation from Canada and the US). This competition complements existing labelling programmes and advances comparable and transparent international test methods that support market transformation programmes. For an emerging technology like light-emitting diodes

(LEDs), this competition enables manufacturers to distinguish themselves and informs policymakers about what is possible for this product group.

This SEAD Global Efficiency Medal competition encourages the production and sale of super-efficient equipment, appliances, electronics, and lighting by identifying the most efficient product in each category in four regions, as well as an overall global winner. The main objectives of the competition are to:

- Maximize energy savings;
- Increase market share of highly efficient products, moving the median of the market to efficient products while staying technology neutral;
- Spur innovation among manufacturers;
- Support test procedure harmonization activities, moving closer to being able to apply the test results of region A to region B;
- Build test lab capacity;
- Provide internationally comparable and transparent test results; and
- Complement and support S&L policies. [1]

When selecting products to be covered by the SEAD Awards, several factors are taken into account. Products should have significant energy savings potential; well-established and accepted test methods (to the extent possible); large energy saving potential between products, which enables products to be differentiated through energy efficiency; and potential to benefit the market – that is, the market for that product has high interest in an award and stakeholders are seeking to differentiate products.

The SEAD competition is a recognition award, not a financial award. SEAD builds awareness of the competition before announcing winning products, and promotes the competition and the winning products. SEAD holds regional and international ceremonies to recognize the manufacturers of winning products, releases a press announcement about the winners, works with partners to promote winning products.

SEAD Lighting Awards Rules Development

To establish the Efficient Lighting competition rules, lighting experts and policymakers in participating regions provided input on lamps and luminaires that are popular, high-volume products in each regional market. Twenty-seven stakeholders from all participating awards regions plus China and Korea provided input over the course of four ninety-minute technical consultation calls to determine the appropriate product categories, technical criteria, and testing methods that were ultimately used for the competition. The rules document also underwent review from lighting industry representatives (including manufacturers, manufacturer associations, and expert technology consultants) to ensure the competition was appropriately scoped for the market.

Lighting Awards Categories

Eight award categories allowed manufacturers to nominate products in a range of sizes, colour temperatures, and lumen outputs.

The original category proposal, shown in Figure 1, was very ambitious in terms of scope, and SEAD quickly realized that there was not enough capacity available to cover all of these categories. Therefore, in consultation with the technical committee, SEAD established subcategories to target specific, high-impact products. Selections were driven by: (1) market considerations, (2) the potential for the market to benefit from the SEAD award, and (3) the relevance of a global award for the product category (for instance, the differing regional requirements for street lighting would have made a global award difficult for the product category). Subcategories were differentiated around luminous flux, color temperature, voltage, and size.

	General Service Lamps	Directional Lamps	Planar Luminaires	Downlight Luminaires	Street Lights
Picture					
Description	Lamps that emit light in all directions (“non-directional”); e.g., A19 shape [a], mains voltage replacement lamp	Lamps that emit directional light; e.g., MR16, PAR38 shapes [b], mains voltage replacement lamp	Recessed ceiling fixtures commonly used in offices for general illumination.	Recessed directional fixtures that deliver light to a space or highlight an object or area.	Outdoor luminaires used for street / roadway lighting and area illumination

Notes:
[a] This was the category for the first round of the L-prize administered by the U.S. Department of Energy [2]
[b] This is the category for the second round of the L-prize administered by the U.S. Department of Energy

Figure 1: Originally Proposed Categories for Consideration for the SEAD Lighting Awards

SEAD Awards competitions seek to include commercially available technologies and emerging technologies that are not yet on the market. Potential emerging technologies that were discussed with the technical consultation committee included organic LEDs, vertical surface cavity emitting lasers (VSCELs), and sulfur lamp technology heated with microwaves. However, the committee indicated that those technologies have not yet been shown to exceed the efficacy of LEDs in terms of lumens/watt. Therefore, these emerging technology categories were not included.

In place of this, a “new technology” category was included for general lighting service lamps that could replace a 100W incandescent bulb. Because of the higher luminous flux, these products are more difficult to make and therefore are not at as advanced a stage as lower wattage replacement lamps.

The final categories for the SEAD Lighting Award are shown in Figure 2. The subcategory specifications – lumen output, color temperature, and size where applicable – were determined based on considerations of the most common products preferred and used in each region.

Regional Awards	GLS Lamps					Directional Lamps		Planar Luminaires	Downlight Luminaires	
	Commercially Available			New Technology		Commercially Available		Commercially Available	Commercially Available	
	≥800 lumens 2700-3000K CCT	≥800 lumens 4000-5500K CCT	≥700 lumens 5500-6500K CCT	≥1500 lumens 4000-5500K CCT	≥1300 lumens 5500-6500K CCT	Low-voltage ≥600 lumens 2700-3000K CCT	Mains-voltage ≥600 lumens 2700-3000K CCT	600mm x 600mm (2ft x 2ft); ≥2000 lumens	≤51mm (2 in) ≥700 lumens 3000K CCT	≥102mm (4 in) ≥1500 lumens 4000K CCT
AUSTRALIA	• 230V	• 230V		• 230V		• 12V	• 230V	•	•	•
EUROPE	• 230V	• 230V		• 230V		• 12V	• 230V	•	•	•
INDIA	• 230V	• 230V	• 230V	• 230V	• 230V	• 12V	• 230V	•	•	•
NORTH AMERICA	• 120V	• 120V		• 120V		• 12V	• 120V	•	•	•
GLOBAL AWARDS	• 230V	• 230V		• 230V		• 12V	• 230V	•	•	•

Figure 2: Final SEAD Lighting Awards Categories

Another possible category mentioned by the committee was industrial lighting, specifically high-bay lighting. This product category provides significant opportunity for LED developments in terms of managing heat given that these are high flux, high power fixtures. This category was not added for the 2014-2015 competition, but SEAD is considering including this category in the next round of awards, potentially to be focused on industrial and outdoor lighting.

Lighting Awards Criteria

To ensure the nominated products were of high quality and had the potential to influence the lighting market, the competition required nominated products to meet 19 quality criteria and to be sold below a cost threshold specified by product and region. These 20 criteria seek to ensure consumers selecting winning products will be satisfied thanks to the reasonable cost and high quality criteria. The competition's criteria (with the exception of the cost criteria) were developed by adapting similar requirements developed and published by the IEA 4E Solid State Lighting Annex [3]. Some criteria were deemed applicable only to particular categories because of the technology used in that category and the desired light service. The criterion for center beam luminous intensity, for example, is only relevant to directional lighting (directional lamps and downlight luminaires).

Although the SEAD Lighting Awards were technology neutral, the technical consultation committee assumed that solid state lighting products would be likely to win most if not all categories. For some of the desired criteria for these products, test methods have not yet caught pace with technological innovation. There is a new test method since published for solid state lighting products with the International Commission on Illumination (Commission Internationale de l'Eclairage, or CIE), CIE TC2-71, but the draft of this test method was not published in time for inclusion in the SEAD Lighting Awards official rules document (which was finalized 9 June 2014).

Cost Criteria

Cost criteria were established based on market research for the average cost of relevant products in each award region. The goal of the cost thresholds was to be low enough that a significant number of consumers would purchase award-winning lamps. If the prices were too high, then the winning products would not be able to bring about market transformation due to low consumer demand.

Prices listed are $/unit	General Lighting Service (GLS) lamp, Omnidirectional, Commercially Available^	Directional lamp, Low voltage	Directional lamp, Mains voltage	Planar luminaire	Downlight luminaire	
					700 lumens	1500 lumens
Australia	$30	$25	$35	$400	$80	$175
Europe	$22	$25	$32	$400	$75	$165
India	$20	$15	$25	$350	$100	$130
North America	$18	$20	$25	$350	$50	$110

^These price thresholds do not apply to the GLS lamp New Technology Class, which has no price threshold.

Table 1: Maximum Allowed Retail Prices for SEAD Award Nominated Products

Efficacy and Light Output Criteria

The criteria in this category that were ultimately required in the competition – indicated in Table 2 with an "x" – were subject to verification testing by a test laboratory selected by SEAD.

Lamp/fixture luminous efficacy (lm/watt)

This criterion – lamp efficacy for the General Lighting Service (GLS) or directional lamps, or complete luminaire efficacy for the downlight or planar luminaires – is the total light output (measured in lumens) of the lamp or luminaire divided by the power consumed (measured in watts). The higher the efficacy value, the more energy-efficient the lighting product. This criterion is of high importance for the consumer and society to save energy and money.

For fixture luminous efficacy, this is also important because if a very efficient light source is installed in an inefficient light fixture, a large part of the light will be lost inside the fixture. As a result, even with a very efficient light source, there will be no efficiency gains or energy saved.

This criterion was the main metric to determine winners for the competition.

Metric	GLS Lamps	Directional Lamps	Planar Luminaires	Downlight Luminaires
Efficacy & Light Output – Subject to verification testing				
A) Lamp/fixture luminous efficacy (lm/w)	×	×	×	×
B) Light output (lm)	×	×	×	×
C) Replacement lamp equivalent wattage claims	×	×		
D) Luminous intensity distribution	×			
E) Zonal lumen density		×	×	×
F) Center beam luminous intensity		×		×
G) Glare luminance (cd/m^2)				
H) Lag start time (ms)				

Table 2: Summary of Potential and Selected Efficacy and Light Output Criteria for the SEAD Lighting Awards

Light output (lm)

This criterion is the total light output (measured in lumens) emitted by the lamp or luminaire. This measurement is required to determine the luminous efficacy and the replacement lamp equivalent wattage claims.

Replacement lamp equivalent wattage claims

The measured level of light output will assist in evaluating manufacturer claims that a given efficient lighting product is an equivalent replacement for a typical wattage incandescent light product. The “equivalent wattage” was as compared to incumbent, traditional technologies.

The technical consultation committee determined this to be an important criterion to include. Experts cautioned, however, that equivalent wattage should not be benchmarked to incumbent technologies, since doing so can produce systems that deliver too much light and result in less energy savings.

Luminous intensity distribution

This criterion describes the measured distribution of a GLS lamp, which is important because many LED products poorly approximate the light distribution of the products they are intended to replace. This criterion ensures better equivalency with regards to meeting consumer expectations when they purchase an LED lamp. This criterion was required for GLS lamps.

Center beam luminous intensity

The technical consultation committee agreed that this criterion was important for assessing the performance of directional lamps and downlight luminaires.

Glare luminance (cd/m^2)

This criterion defines total luminance levels where the visual contrast between task and light source are so high that the task cannot be distinguished – the amount of light makes it physically painful or difficult to work. This criterion was considered potentially important for street lighting, as glare is unsafe for drivers and can increase light pollution. There is also some indication that products with strong glare impede work efficiency in offices.

To test for glare luminance, the Design Lights Consortium has a method that the IEA-4E SSL Annex has been using for glare measurements. However, it is not widely accepted. Although this criterion was thought to be important, in the absence of available quantifiable test methods it was excluded from this competition.

Lag start time (ms)

This item measures the amount of time for a lighting product to begin emitting light after power is turned on. It is important that the starting time of a lighting product is very short, both for emergency situations and for consumer acceptance.

This criterion was eliminated from this competition because it was not believed to be an issue for LED lighting (which it was assumed would be the technology behind winning products), and because although there is a test method for compact fluorescent lamps (CFLs), there is no existing test method for LEDs.

Color and Light Quality Criteria

The criteria in this category that were ultimately required in the competition – indicated in Table 3 with an "x" – were subject to verification testing by a test laboratory selected by SEAD.

Metric	GLS Lamps	Directional Lamps	Planar Luminaires	Downlight Luminaires
Color & Light Quality – Subject to verification testing				
A) Color rendering (CRI and R9)	×	×	×	×
B) Correlated color temperature (CCT)	×	×	×	×
C) Chromaticity tolerance (Duv)	×	×	×	×
D) Minimum power factor	×	×	×	×
E) Flicker (flicker index)	×	×	×	×

Table 3: Summary of Potential and Selected Color and Light Quality Criteria for the SEAD Lighting Awards

Color rendering index (CRI and R9)

Color rendering is a measure of how similar object colors appear under one light source as compared to the object colors under a reference light source (usually an incandescent light or daylight). Color rendering is very important for consumer satisfaction with a lighting product. R9 determines the accurate rendering of the color red, which is not used in the calculation of the CRI.

This criterion was required for all nominated products.

Correlated color temperature (CCT)

This criterion was a requirement for all nominated products. The CCT metric helps consumers (1) select the appropriate product depending on their light color temperature preference, and (2) match light color temperature across different manufacturers' lighting products. This way, when different manufacturers' light products are used in the same space, there is not an unintended mix of cool-white lighting with warm-white lighting.

Because most lamps are currently based on blue LED pumping of phosphor – a technique that results in cooler color temperatures – there is less efficacy at warmer color temperatures. Therefore, the competition created separate subcategories of CCT ranges for cool white and warm white lamps.

CCT was determined to be a necessary defining factor in the development of subcategories, focusing on the most popular CCT in the market and requiring lamps to fall within a certain defined range.

Luminaires are generally designed around a specific CCT, for example, 3000K, 4000K, or 5000K. Luminaires would exhibit different efficacies based on the different light engines, so the subcategory was defined at the most popular color temperature with a tolerance around that CCT. For these luminaires, it would not be fair to compare them with each other if they had different CCTs.

All CCTs had an allowed tolerance, such that any lamp or luminaire claiming to have a certain CCT would not deviate from that requirement by more than the IEC standard allows.

Chromaticity tolerance (Duv)

This criterion is critical in commercial or professional settings and also important for household applications. For professional products, this measurement makes sure that products are in line with any color temperature or light quality claims, resulting in consistent color between fixtures that illuminate a hotel lobby or office space. This criterion also has considerable cost and complexity to test.

Minimum power factor

Power factor is the ratio of the real power flowing to the load over the apparent power of the circuit. For electrical power suppliers, this can be of very high importance depending on the power network. However, for residential customers there has not been established any significant relation between the power factor of small electronic loads like efficient lighting and the grid power factor.

This criterion was a must have. Although products tend to have sufficient power factors, a minimum requirement would prevent power factors falling to unacceptable levels.

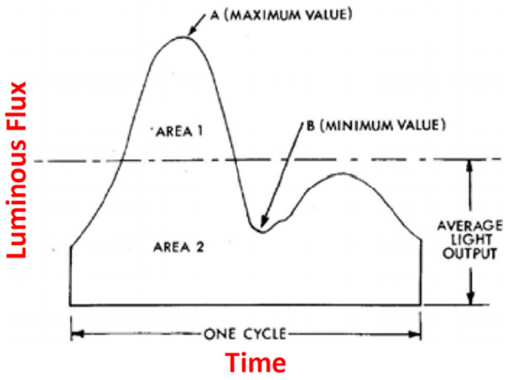
Flicker (flicker index)

This criterion was considered to be important to include, but it currently is not used in any regulatory processes. This is a notable topic in government R&D programs, such as the US DOE CALiPER (Commercially Available LED Product Evaluation and Reporting) and GATEWAY programs. [4]

For the emerging market of LEDs that work on alternating current, the chip goes on and off as the current goes up and down, which sometimes can create a visible flicker. LEDs operating on AC have an advantage in that there are no overhead losses associated with the drivers, so they have greater potential for efficacy and high efficiency performance. In that case, flicker reduction would be a must have for this program, because it would reflect poorly on the SEAD awards to award a product that is the most efficient in the market but had noticeable flicker.

After extensive discussion and follow-up correspondence, it seems that there is no established test method for flicker. Policymakers, technical experts, and industry alike noted that this is a critical issue without an established test method. The International Energy Agency (IEA) Implementing Agreement for a Co-operative Programme on Energy Efficient End-Use Equipment (4E) SSL Annex defines flicker measurement as follows:

> "This criterion measures the perceived photometric "flicker" of a light source. Flicker index defined by (Area 1 / (Area 1+Area2)); replaced by new metric under development by IEEE PAR1789 which accounts for frequency, when available.



This is an important item for both consumer satisfaction and consumer acceptance of SSL products. Some consumers may have severe health reactions to flickering light sources of certain frequencies ranging from low-grade headaches to extreme seizures. Flicker can also make rapidly moving objects seem like they are standing still, or leave after images of bright points in the visual field. The requirements minimize these stroboscopic effects."

Lifetime Criteria

For the criteria in this category that were ultimately required in the competition – indicated in Table 4 with an "x" – manufacturers were required to submit supporting documentation verifying their claims.

Metric	GLS Lamps	Directional Lamps	Planar Luminaires	Downlight Luminaires
Lifetime – Supporting documentation required				
A) Minimum rated lamp lifetime (B_{50})				
B) Minimum lumen maintenance (time to L_{70})	×	×	×	×
C) Color maintenance (Δ u'v' at 6,000h)	×	×	×	×
D) Endurance test	×	×	×	×
E) Warranty duration	×	×	×	×

Table 4: Summary of Potential and Selected Lifetime Criteria for the SEAD Lighting Awards

Minimum rated lamp lifetime (B_{50})

Lifetime is typically defined as the amount of time that it takes for 50% of a statistically significant sample to fail (also known as B_{50}). It is unrealistic to measure very long lifetimes for lighting products, but having a credible B_{50} estimation is very important as lighting products with longer lifetimes must justify their higher initial cost. If efficient lighting products are able to meet their lifetime claims, they can cut long-term energy consumption and save the consumer money over the life of the product even if the up-front cost is higher.

While the technical consultation committee would have like to include this criterion, SEAD did not have enough time or resources for testing. The competition elected instead to use lumen maintenance as a surrogate for lifetime.

Another proposed approach was to look instead at early failures from electronics. A criterion was proposed that would require less than 5% failures (or some figure) for a test of 1000 or 2000 hours. This would still present a potential challenge with the number of products needed to test, but this would test for early product failure which is a big issue from the perspective of purchasers. Due to limited time and resources, SEAD did not elect to go forward with this proposed variation.

Minimum lumen maintenance (time to L_{70})

Lumen maintenance is the percentage of a lighting product's measured light output after a period of time compared to that light product's initial total light output. This criterion helps the consumer determine how long it will take a lighting product to degrade to the point that it is no longer useable. High lumen maintenance over time helps to justify the higher initial cost of efficient lighting products.

This criterion was determined to be a requirement, with the suggestion again that the competition refer to test reports from independent test laboratories rather than test for this criterion given time and resource constraints. Participants also noted that this approach had the added value of preventing SEAD from taking too long to evaluate products, leading to awarding products that would no longer be on the market.

Color maintenance (Δ u',v' at 6,000h)

This criterion measures the consistency of color over time as a lighting product ages. It was determined to be a must have, but again it was deemed impractical for SEAD to perform the required 6,000 hours of testing. As with minimum lumen maintenance, for this criterion the competition relied on test reports from independent test laboratories, provided by manufacturers, to mitigate time and resource constraints.

Endurance test

This criterion requires that a lighting product is rapidly switched on and off to simulate how a product will be used over its lifetime. It requires that a test is carried out to stress a lighting product over a short period of time to determine the failure rates of a product. A stress test like this one can help verify that a lighting product will not fail when installed and used in a consumer application. This criterion was required via manufacturer submission of independent test results.

Warranty duration

It is very important that consumers have a guarantee that SSL products will perform as claimed. Therefore this criterion was determined to be critical, and was included as a minimum warranty requirement of three years. This was coupled with a requirement that products have rated lifetimes of at least 15,000 hours. However, that rated lifetime was not confirmed through verification testing.

Health and Environment Criteria

For the criteria in this category that were ultimately required in the competition – indicated in Table 5 with an "x" – manufacturers were required to submit supporting documentation verifying their claims.

Metric	GLS Lamps	Directional Lamps	Planar Luminaires	Downlight Luminaires
Health & Environment – Supporting documentation required				
A) Safety requirements	×	×	×	×
B) Hazardous substances	×	×	×	×
C) Blue Light Photo-biological hazard class	×	×	×	×
D) Compatibility with controls			×	×
E) Recyclability (%)				
F) Harmonic distortion				

Table 5: Summary of Potential and Selected Health and Environment Criteria for the SEAD Lighting Awards

Safety requirements

This criterion, which specifies that a product meets electrical safety requirements and marking requirements, was very important to many participants in order to protect the program against awarding an unsellable product. However, safety markings vary by national markets, making it complicated to specify this criterion internationally. Ultimately, a consensus formed around requiring products to meet safety requirements in the country where it is entered (and therefore sold).

The competition would not have to test for safety, but manufacturers should show that they have achieved the appropriate safety standards as minimal criteria for application. In any region without a safety mark, manufacturers would be required to submit evidence that the product meets safety requirements in the market.

Hazardous substances

This criterion is about regulating hazardous substances, focusing on materials that go into making the product. It was included as a requirement. In Europe, for example, this criterion would indicate that products must be RoHS compliant.

Blue Light Photo-biological hazard class

This criterion is very important for consumer safety, as high frequency blue light can cause irreparable damage to eyesight. It was determined to be essential for domestic applications (residential and commercial). It was also noted that stakeholders in some communities expressed concerns regarding ultraviolet (UV) and blue light in lighting products because of adverse health effects on lupus sufferers.

Compatibility with controls

This criterion looks at whether a product is compatible with dimmers, which normally expect a resistive load in the socket, and controls. Dimmer compatibility is of high importance for the consumer as new lighting products often are not completely compatible with commonly available dimmers thus making it difficult for consumers to use these efficient products in existing lighting systems. As manufacturers are still trying to define and adopt a new dimming standard, the dimmer compatibility of new lighting products is likely to continue to be a problem.

This criterion could also be complicated to measure and verify due to the limitations of standards. Ultimately the committee determined this was relevant only for certain product categories.

Recyclability (%)

While this criterion would have been nice to have, no clear method exists on how to quantify recyclability. Some methods proposed included determining the per cent of components that could be recycled, or giving some bonus credit to products that were designed so that they could be disassembled and then more easily recycled. Ultimately this criterion was not included in the competition.

Harmonic distortion

Harmonic distortion measures how the lighting product will affect the quality of the electrical utility's grid. This criterion would be a must have for street lighting products, but is not essential for residential and commercial lighting.

Additional Potential Criteria

Lumen maintenance of integrated lamp/luminaire

This criterion is similar to the lumen maintenance criterion, but would test the integrated product rather than the LEDs on their own. However, this would have required the availability of new test method documents that were under development from the Illuminating Engineering Society at the time the rules were finalized: IES-LM-84 and IES-TM-28.

Standby

The technical consultation committee recommended consideration of a criterion for maximum standby and wireless power for the general service category, or for a separate category for controllable domestic lighting. With LED lighting that is capable of being controlled remotely, there is a real possibility that every light bulb in a future home could experience standby losses. In order for LED products to be perceived as more valuable, features like remote control and smart-phone application control are being incorporated into many lamps. These features mean that when the lights are turned "off," they will actually be in standby mode all the time waiting for instruction.

Including this criterion would ensure that nominated LED products had taken standby losses into consideration.

SEAD chose to leave out this criterion, as it is not yet included in national policies, but to request this data from manufacturers for nominated products and to include tests for standby power usage for tested lighting products.

Work is underway to further investigate how best to include this criterion in policies for lighting products, for instance in the IEA 4E SSL Annex [5], the IEA 4E Electronic Devices and Networks Annex (EDNA) [6], and the G20 Energy Efficiency Action Plan [7].

Tropical Criteria

The technical consultation committee also considered including criteria for performance in tropical environments, such as those developed by lites.asia [8]. These additional rigorous requirements were put in place because products were not surviving in tropical markets due to these difficult operating conditions. These tests subject lamps to:

- An over voltage test, where the rated voltage is exceeded by 10% and the lamp must be able to deliver the rated lumen output during 15 minutes of operation;
- An under voltage test, where the rated voltages is dropped by 30% and the lamp must be able to operate;
- A high temperature and humidity test, where the lamp is exposed to 85°C and 85% humidity for 500 hours and then has to have not less than 10% lumen depreciation relative to the original test; and
- Ingress protection and heat sink maintenance tests.

These difficult operating conditions may be applicable in certain climates and markets, but not all (e.g., not in the EU). Thus applying these criteria to all products in the SEAD Awards would lead to winning products in the EU that were more expensive, bulkier, and maybe less efficient in order to meet locally unnecessary tropical test conditions. However, the inclusion of regional requirements would also prevent those categories from having a comparable international winner.

Ultimately, SEAD chose not to include the tropical criteria in this competition.

Winning Products

Regional and global winners have been determined for the GLS categories. The global winning product in the commercially available, 60W replacement category (>800lm) with 2700-3000K CCT had an efficiency of 121 lm/W. Replacing inefficient general service lamps with the SEAD Global Efficiency Medal Award winner would reduce electricity consumption in this end-use application by 82%. This would provide annual savings of approximately 850 TWh (terawatt hours) of electricity, or approximately 426 million tonnes of CO_2.

At the time of publication the other award category winners were still being determined.

Conclusions

A team of 27 lighting experts and government representatives from 8 countries were able to identify 20 common efficiency, quality, and cost criteria across 8 residential and commercial lighting product categories. These 8 lighting product categories covered the largest global market applications. The 20 common criteria were used to ensure *high-quality and market ready* efficient lighting products were eligible to win the competition.

References

[1] Ravi et al 2013. *Policy into practice: the SEAD global efficiency medal*. eceee summer study proceedings. Available for download at: http://proceedings.eceee.org/visabstrakt.php?event=3&doc=6-180-13

[2] The L-Prize is a technology competition sponsored by the US government, designed to spur lighting manufacturers to develop high-quality, high-efficiency SSL products that set leading-edge performance benchmarks for industry. More information is available at: http://www.lightingprize.org/

[3] IEA 4E SSL Annex, 2012. Available for download at: http://ssl.iea-4e.org/task-1-quality-assurance/performance-tiers

[4] The US DOE launched the CALiPER program in 2006 to address a need for unbiased, trusted product performance information in the early years of SSL. DOE GATEWAY demonstrations enable detailed LED product evaluation and hands-on experience that cannot be replicated in a lab. More information on CALiPER is available at: http://energy.gov/eere/ssl/caliper-testing and on GATEWAY at: http://energy.gov/eere/ssl/gateway-demonstrations

[5] More information on the IEA 4E SSL Annex is available at: http://ssl.iea-4e.org/

[6] More information on the IEA 4E EDNA is available at: http://edna.iea-4e.org/

[7] More information is available online at: http://www.g20australia.org/sites/default/files/g20_resources/library/g20_energy_efficiency_action_plan.pdf

[8] http://www.lites.asia/downloads/tropical-performance-criteria

Nigeria Lighting Compliance Study

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Abstract

One of the major challenges witnessed by the on-going efforts to promote energy efficiency in Nigeria is the proliferation of substandard lighting products in the market. Stakeholders complained that energy saving lamps such as compact fluorescent lamps (CFLs) do not last as long as the expected life span; some last for less than a month. As a result, many stakeholders are discouraged using these products. With the recent installation of light testing analysing machines in the Standard Organization of Nigeria (SON) and the National Centre for Energy Efficiency and Conservation (NCEEC), supported by the GEF-UNDP Energy Efficiency Programme, the Project Team embarked on a study to collect data that will guide relevant authorities to address these challenges. The study was conducted to collect baseline information that will form the bases for monitoring and measuring success when the lighting market is fully regulated; to identify CFLs and other energy efficient lamps in the Nigerian market that do not meet the newly approved lighting standards; and to make available adequate data to the relevant agencies of government to properly inform consumers on the lighting products that meets the Nigerian standard. To ensure that all lighting products are captured, samples of light bulbs were collected in cities where the two major ports in Nigeria are located and in cities where the major markets in Nigeria are located. The samples were taken to the laboratory at NCEEC for testing. The objectives of this paper are to present the results of the study and proffer strategies for addressing the challenges posed by the proliferation of substandard energy saving products in any market.

Introduction

One of the major challenges witnessed by the on-going efforts to promote energy efficiency in Nigeria is the proliferation of substandard lighting products in the market. Stakeholders complained that the energy saving lamps such as compact fluorescent lamps (CFLs) available in the Nigerian market do not last as long as the expected life span; some last for less than a month. As a result, many stakeholders are discouraged using these products. On the average, good quality CFLs are designed to last for a period of about 4 years. If this is problem is not addressed, it will greatly hinder all efforts to promote the use of energy efficient equipment in Nigeria.

With the development of the minimum energy performance standard (MEPS) for CFLs and the installation of light testing analyzing machines in the Standard Organization of Nigeria (SON) and the National Centre for Energy Efficiency and Conservation (NCEEC), supported by Global Environment Facility (GEF) and the United Nations Development Programme (UNDP), the SON is set to fully regulate the lighting appliance market. The need to build confidence in stakeholders in Nigeria to use energy saving bulbs is critical to transform the market. It is imperative for the relevant authorities in Nigeria such as the SON and the Consumer Protection Council to be properly informed of the lighting products that meet the newly set standard so that they can advice consumer appropriately.

To precisely address these challenges in the lighting sector in Nigeria, a study was conducted to collect baseline information that will form the bases for monitoring and measuring success when the lighting market is fully regulated; to identify CFLs and other energy efficient lamp in the Nigerian market that do not meet the newly approved lighting standards; and to make available adequate data to the relevant agencies of government to properly inform consumers on the lighting products that meets the Nigerian standard.

Data Collection and Analysis

Samples of light bulbs were collected from February to September 2013 in cities where the two major ports in Nigeria are located – Lagos (Lagos State) and Port Harcourt (River State) and in cities where the major markets in Nigeria are located – Aba (Abia State), Onitsha and Awka (Anambra State), Kano (Kano State) and Abuja (Federal Capital Territory). As at the time of data collection, the Project Team was unable to collect samples of light bulbs from Maiduguri, northern-eastern Nigeria because of the state of emergency declared by the Nigerian government in that region. At the point of collection, the samples of light bulbs were properly labelled. A total of 1500 lamps were collected and tested in the laboratory of the National Centre for Energy Efficiency and Conservation, University of Lagos.

Table 1: Sample size distribution

Location	Number of Samples	Percentage
Port Harcourt	117	7.8
Kano	190	12.7
Abuja	392	26.1
Onitsha & Awka	263	17.5
Aba	236	15.7
Lagos	302	20.1
Total	**1500**	**100.0**

Samples of light bulbs were collected in the open market and organized grocery market. In this context, the open market is a cluster of shops dealing on a particular product or variety of products. In this type of market, the number of shops could range from as few as two to reach several hundreds. In many cases, in an open market, there are sessions of the market devoted to the sales of a particular product. A good example of an open market is the popular Alaba International Market in Lagos State. The organized markets are large departmental shops where different kinds of goods are sold. In the organized market, there are usually sessions of the shop dedicated to a particular product.

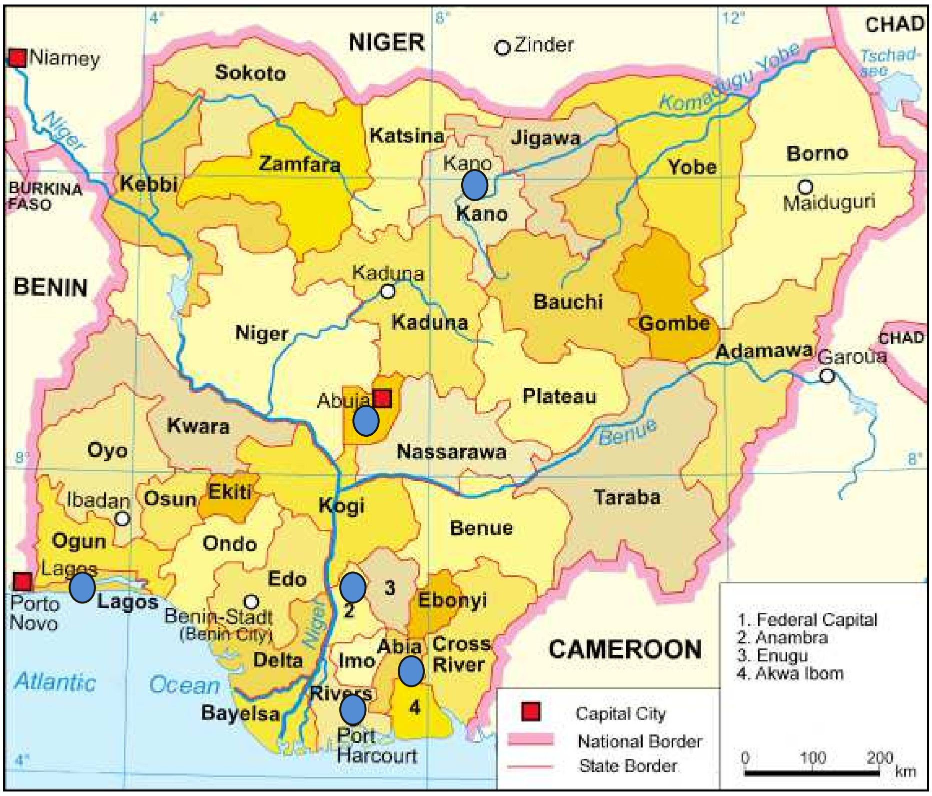


Fig. 1: Locations where samples were collected

The lamps were tested according to IEC 60969 standard testing procedures as outlined in the following session.

Marking

Visual check was conducted on the pack of every lamp sample. The following parameters in Table1 are required on the pack of every lamp sample according to IEC 60969. A form is allocated to each lamp for recording the parameters available on each pack for comparison with IEC 60969 requirements.

Table 2: IEC 60969 marking requirements

Parameter (Rated)	**Product**	**Product Packaging**	**Product datasheet or leaflet**
Initial luminous flux of the lamp (lumens)	-	X	X
Beam angle (degrees) and centre beam intensity (candela) for reflector lamps	-	X	X
Initial efficacy (lumens/Watt)	-	-	X
Correlated colour temperature (kelvin)	X	X	X
Colour rendering index	-	X	X
Chromaticity coordinates	-	-	X
Median lamp life (hours)	-	X	X
Lumen maintenance (%) including operating hours at which lumen maintenance value(s) are claimed	-	-	X
Switching withstand (number of cycles)	-	-	X
Special operating requirements (dimming, orientation and restricted operating temperature range)	-	X	X
Starting time (seconds)	-	-	X
Low temperature starting time (seconds) and temperature if lower than -10°C	-	-	X
Run-up time (seconds)	-	X	X
Displacement factor	-	-	X
Distortion factor	-	-	X

Aging Test

The lamps were pre-conditioned by operating them at controlled conditions for 100 hours using the DJ4000 Aging–life Testing Machine.

Parameter Analysis

On completing the aging test, the lamps are immediately transferred to the YF-1000 complete set of light analysis machine. The YF-1000 comprises of the following components: DPS1010PWM Type AC Power Supply; HAAS-1200 High Accuracy Array Spectroradiometer; PF9811 Digital Power Meter; PHOTO-2000F Rapid Recording Photometer; 1.5 m Integrating Sphere; and YF1000 Cabinet. Each bulb is fixed to a lamp holder in the 1.5 m Integrating Sphere within 2-3 minutes after the aging test. It is allowed to stabilize for 20 minutes in the sphere.

The results of the different parameters were read from a computer connected to the entire unit of the YF-1000 machine. For all the parameters tested in this study, the power supplied to the testing unit is alternating current (AC) from the electricity grid which is measured and regulated by the PF9811 Digital Power Meter. For each sample, the following parameters were tested: Colour Parameters - render index, colour temperature (K) and purity; Photo Parameters – flux and efficacy; and Electrical Parameters - voltage range, current range, wattage and power factor

Result of Study

Type of Market and Brand Names

The 1500 different samples of light bulbs collected during the study represent 206 different brand names. A total of 87% of the samples were collected in the open market while 13% were collected in the organized market.

Aging Test

Out of the 1500 samples collected during the period of the study, a total of 237 (representing 15.8 % of the total sample sized) failed the 100 hour aging test while 1263 (84.2%) were fit enough to proceed to the parameters test.

Countries of Origin

The countries of origin of 334 (22.3%) of the samples collected is unknown, that is to say that the manufacturers did not declare the countries of origin either on the pack or on the products. Majority of samples originated from China (72.6%), followed by the United Kingdom (1.6%) and Vietnam (1.2%) as shown in Table 3.

Table 3: Countries of origin of light bulbs

Country	Number	Percentage
China	1089	72.6
Hungary	14	0.9
United Kingdom	24	1.6
Vietnam	18	1.2
Japan	7	0.5
Netherland	4	0.3
Nigeria	1	0.1
Poland	1	0.1
Germany	6	0.4
Malaysia	1	0.1
Canada	1	0.1
Unknown Origin	334	22.3
Total	**1500**	**100**

Prices of Products

The prices of the products vary and are directly proportional to the rating of the products. The prices of most of the product (69.4 %) range from ₦100 to ₦ 500 while 19.6% of the products are sold for between ₦ 500 to ₦ 1000, 1.7 % is sold from ₦ 1501to ₦ 2000 and less than 1% is sold for over ₦ 2500 (Fig. 2).

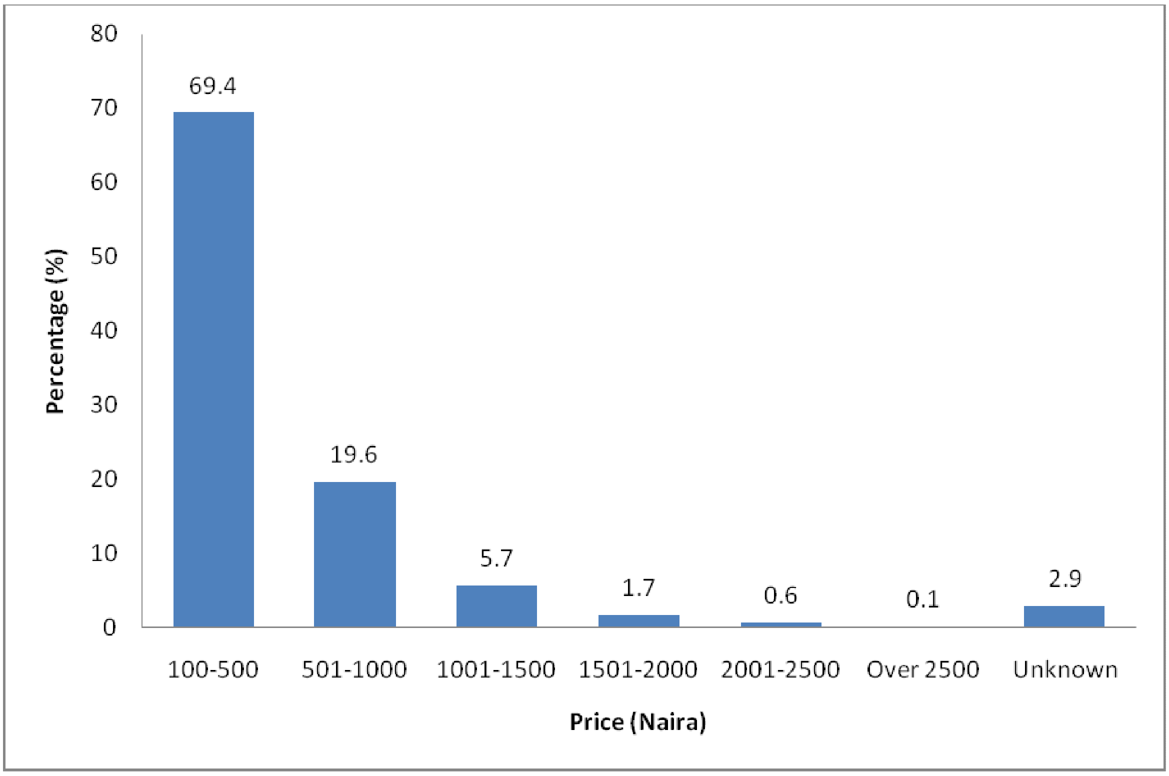


Fig. 2: Prices of light bulbs (approximately ₦200 is equivalent to US 1$)

Type of Market

A total of 83% of the products were collected from the open market while 12% of the products were collected from the organized market (Fig. 3).

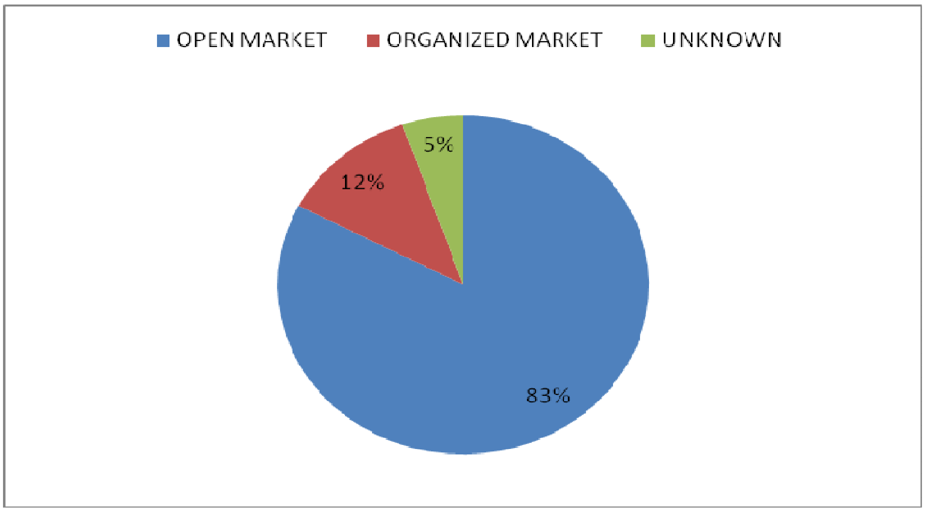


Fig. 3: Samples and type of market

Type of Base

The samples collected have three major types of base – the screw base with larger diameter (E27) was the most abundant (59.6%), followed by the ones with the pin base (B22) which accounted for 37.5% and the one with the screw base smaller in diameter than the E27 (E14) and this accounted for only 2.9% of the samples (Fig. 4)

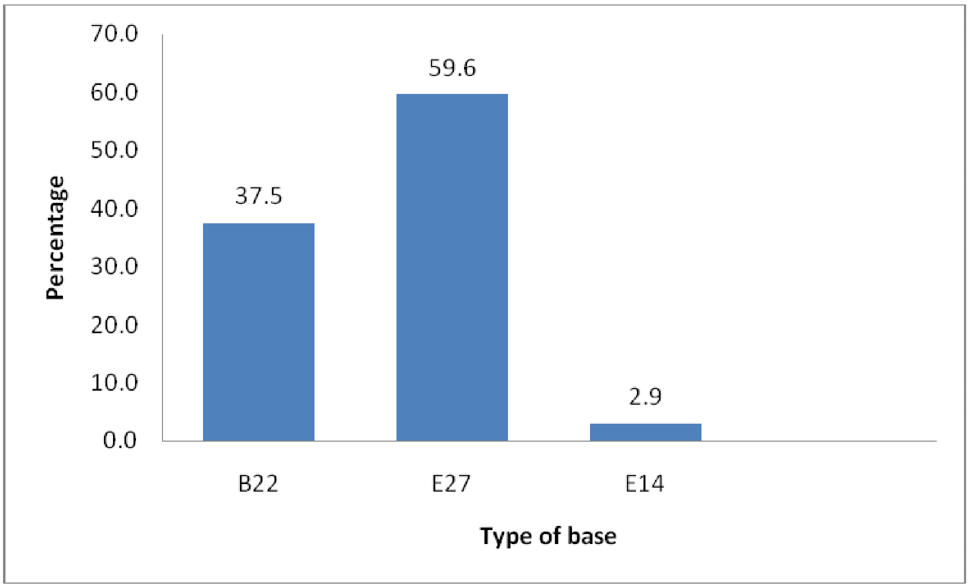


Fig. 4: Type of base

Voltage

According to the Nigerian Industrial Standard (NIS747:2012), the rated voltage of light bulb is defined as the voltage or voltage range inscribed on the lamp or the pack, while the test voltage is the voltage at which test was carried out on the lamp. The rated voltage were marked on over 99% of the total lamps collected (Table 3.1). A total of 85% of the lamps operated efficiently within a voltage range of 100V to 250V.

Table 4: Rate voltage

	No. of Lamps	Percentage
Not marked	4	0.3
Marked	1496	99.7

Power Factor

The power factor of an electrical system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit. A load with a low power factor draws more current than a load with a high power factor for the same amount of useful power transferred. A total of 94 % of the manufacturers of the samples collected did not inscribe the power factor of their lamps either on the pack or on the products (Fig. 5).

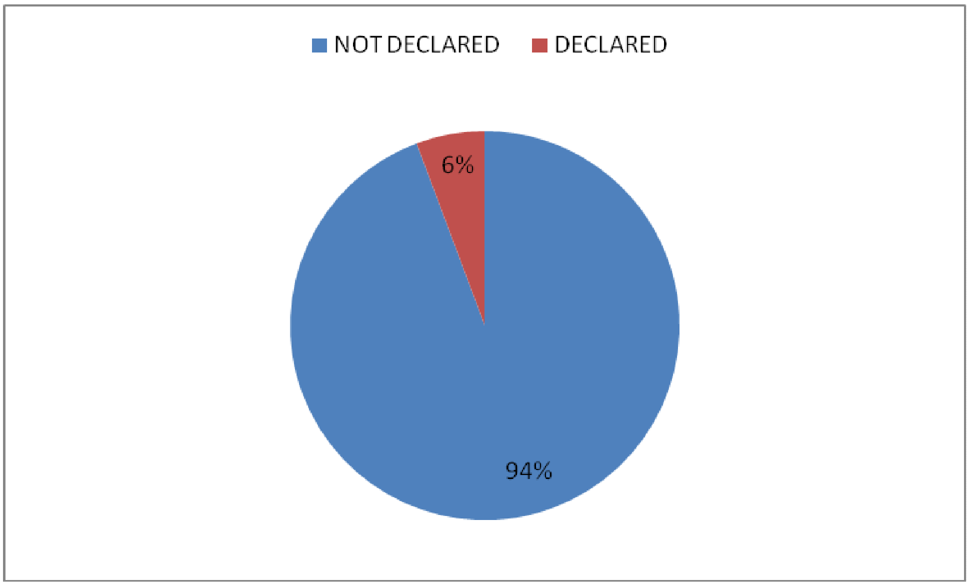


Fig. 5: Power rating inscription on products

When the power factor of the products were measured using the light analyzing machine, the power factor of 83% of the products were less than 0.85 and only about 1% of the products had power factor of 0.85 and above. About 16% of the samples did not pass the 100 hour aging test and as such they could not be subjected to the parameter test.

Power Rating

The rated wattage is the wattage marked on the lamp. Manufacturers of light bulbs are expected to inscribe the power rating (in watt) of their products either on the pack or on the product. The power rating was inscribed on 1358 (90.5 %) of the samples while 142 (9.5 %) of the products did not have the power rating inscribed on them (Table 3.2).

Table 5: Power rating inscription

	No. of samples	Percentage
NOT DECLARED	142	9.5
DECLARED	1358	90.5

Many of the manufacturers inscribed the power rating of their bulb on the pack and some of them inscribed the rating on the pack. When the power rating of the bulbs were measured in the laboratory, the measured rating of 1,251 (83.3%) of the bulbs were below 60W. The newly approved Nigerian Standard on Lighting (NIS 747: 2012) has stipulated that the rated power of tubular fluorescent and other gas discharged lamps should not exceed 60W. It was also observed that in many cases, there were huge differences between the declared values and the measured values.

Luminous Efficacy

The luminous efficacy of a light bulb is the ratio of the luminous flux to the power rating. It is a measure of the efficiency at which the lamp provides visible light from the energy input. Manufacturers of 1425 (95%) of the samples did not declare the luminous efficacy of their products either on the packs or on the products while only 75 (5%) declared their luminous efficacy (Fig. 3.4).

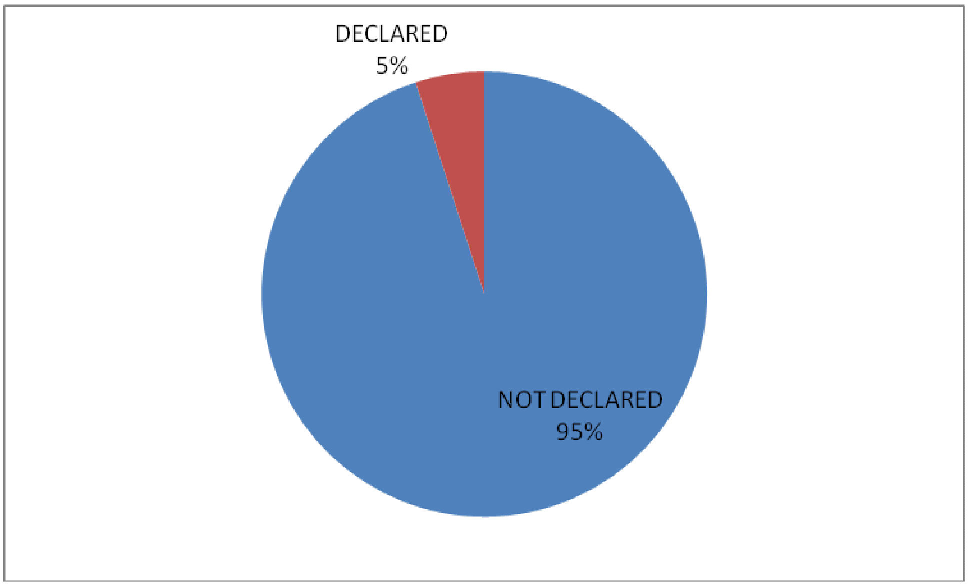
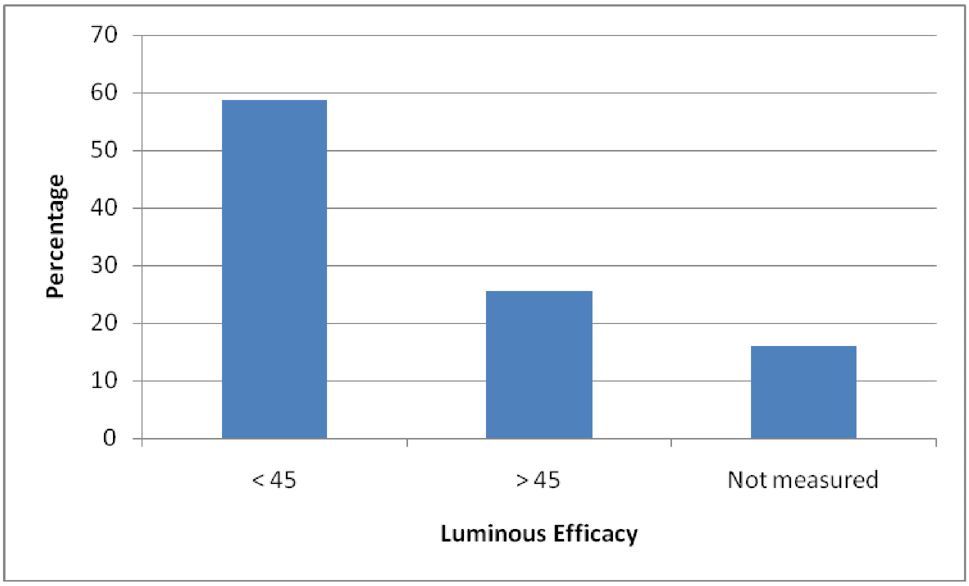


Fig. 6: Luminous efficacy

When the luminous efficacies of the lamps were measured, the efficacy of 58.6% of the samples was less than 45 lm/W while the efficacies of 25.5 % of the samples were equal to and greater than 45 lm/W.



Discussion and Conclusion

The current study revealed that there are 206 different brands of compact fluorescent lamps in the Nigerian market and yet none of these products are manufactured in Nigeria. From the previous study conducted under the Energy Efficiency Programme, it was revealed that the Nigerian market depends solely on the importation of light bulbs; as at the time of this study, there is no manufacturing facility for CFLs in Nigeria. Further investigation revealed that many of the CFLs are manufactured off-shore and branded by Nigerian businessmen and not the manufacturing company. This implies that many of the CFLs in the market are branded by the individual importers. At the early stage of the Energy Efficiency Programme, during consultations with stakeholders, it was revealed that some Nigerian businessmen go to countries like China and India to buy substandard products and bring them into the Nigerian market (UNDP-GEF EE Project Document).

It is alarming to know that up to 15.8 % of the total samples collected during the current study did not pass the 100 hour aging test. This implies that this set of light bulbs will burn out within 14 days if used for an average of 8 hours a day. This has been a major barrier to the energy efficiency campaign in Nigeria. At the early stage of the Energy Efficiency Programme in Nigeria, many stakeholders complained that the energy saving bulbs in the market do last as long as the stipulated time. A good CFL is expected to last for 6000 hours to 8000 hours. As a result of this anomaly, many Nigerians do not have faith in the use of energy saving lamps. Many of them will prefer to continue using the incandescent bulbs instead of buying energy efficient bulbs. The result of the aging test already suggests that about 16 % of the CFLs in the market are substandard. The newly approved standard in Nigeria stipulated that CFLs should last for a minimum of 6000 hours

Over 70% of the samples collected during the current study originated from China. The countries of origin of some of the products were unknown (22.3 %). The study revealed that Less than 5 % of the products were manufactured in other countries. This concurs with the previous finding during the development of the EE Programme that many Nigerians businessmen go to China and ask the Chinese manufacturers to make CFLs to their specifications using price as major consideration. In a situation where the government regulations do not define specifications for light bulbs, it is inevitable that manufacturers supplying the Nigerian market will manufacture to their own specification irrespective of the quality. This barrier is being addressed with the new regulation (MEPS) for CFLs put in place by the Standard Organization of Nigeria (SON) with support from the Global Environment Facility and the United Nations Development Programme (UNDP). The Nigerian standard has clearly stated that the country of origin of lighting products should be inscribed on the product or on the pack.

Price is a very strong economic factor influencing the demand for goods and services. In the current study, it has been revealed that the prices of over 70% of the products fall between N100 and N500. Price is a parameter to determine the quality of products. From the interaction with manufacturers of lighting products, it has been found that the higher the quality of light bulbs, the higher the prices of these products. For example, the cost of good lighting product that meets the required standard set by the Nigerian authority ranges from N600 and above. Premised on this, the result from the current study suggests that the products that cost below N600 are most likely to be substandard.

Many Nigerians live below the poverty line of $2 per day and as such price will be an important factor that informs their decision to purchase lighting products. Many are not able to afford the cost of energy efficient appliances which are sometime more expensive than the less efficient ones. This is the reason why many Nigerians go for low-cost goods. The proliferation of imported low-cost and substandard appliances may hinder the use of efficient appliances. The reason is that these products are cheaper compared to the high quality ones and are easily available in market. Because of the price factor, the high quality efficient lighting products may be unable to compete with substandard ones in the market. The current study has revealed that the Nigerian market is flooded with all kinds of substandard lighting appliances. Many consumers will prefer to go for the cheaper ones not minding the long-term benefit of using efficiency bulbs (Uyigue et al, 2009).

The types of market where these products are purchased also have a lot to do with the quality of the products. In the current study, 83% of the products were collected from the open market. Most of the products that do not meet the Nigerian standards were collected in the open market. The current study has revealed that good quality lighting products are most likely to be found in the organized grocery shops. In the current study, the lamps with the E27 base were the most abundant accounting for 57% of the samples. Most of the products operated within a voltage range of 100-250 V.

From the visual check on the pack of the samples, many of the products did not meet the newly developed standard for lighting products in Nigeria. It is require for manufacturers supplying the Nigerian market to inscribe the parameters of lighting products on the pack of the product and on the products. The study showed that 95% of the products do not have the luminous efficacy inscribed on the product or on the pack. Similarly, the power factor is not inscribed on 94% of the samples. From the Nigerian standard, these numbers of product have deviated from the Nigeria minimum standard for lighting products.

Check-testing has been carried out in many developed countries, for instance, it has been done in Australia since 1991 (Grubbert, 2001). In Nigeria, in addition to the check-testing, it is important for the Nigerian authority to create a platform where they can interact periodically with importer and manufacturers of lighting products. There is need to communicate the newly approved lighting standard in Nigeria with importers and manufacturers of lighting products. The Nigerian authority should also invest in awareness creation, to let the Nigerian populace know of the economic benefits of purchasing good and quality lighting products. This, combined with the check-testing will expedite the process of eliminating substandard lighting products from Nigeria.

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Smart Meters and Feedback Systems

Identifying the opportunities for ICT based energy demand reduction in family homes

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Abstract

It is widely recognised that the residential sector will play an important role in achieving UK national targets for reductions in energy consumption and CO_2 production. This will be achieved through efficiency gains in devices, improvements to the building fabric and systems, more effective utilisation of devices and through accepting lower levels of comfort and convenience. Home Energy Management Systems (HEMS) and other Information and Communication (ICT) based solutions are attractive because they offer help in managing device/systems and can be applied to reducing consumption while (potentially) mitigating the impact on comfort and lifestyle. This paper attempts to quantify the energy reduction potential for HEMS/ICT through a systematic treatment of monitoring data from real family homes. The analysis describes for the first time the notion of the 'Reduction Effort Balance' that exists between capital expenditure and acceptance of less comfort and convenience and it is demonstrated that HEMS/ICT could influence up to 50% of the possible energy demand reduction. The findings also suggest that it is highly unlikely that energy reduction targets will be met without changes to occupant lifestyle

Introduction

The UK targets for energy demand reduction are challenging and will impact energy consumption in the built environment in particular. Domestic energy consumption accounts for about 30% of the UK total and hence forms an important target area for these measures [1]. Energy reduction in homes, however, is not just a matter for retrofit measures, it depends on a number of variables such as: appliance ownership, control settings for space heating, hot water and appliance use patterns and the number of people in the home [2, 3, 4, 5, 6, 7, 8].

Better space heating control is a key factor in achieving significant energy demand reduction and there are currently 'smart home' systems on the market such as Control4 or VeraEdge Z-Wave Home Automation which increase the control users have over their consumption [9, 10]. Smarter heating controls, can give real time feedback and/or automatic adjustment of indoor temperatures. Devices such as the Nest thermostat try to predict occupancy to enable wasted heating to be minimised. Advanced home energy management systems (HEMS) such as Honeywell's Evohome aim to make the control and setting of heating parameters more straightforward, empowering the user to take energy saving action [11, 12].

This paper forms part of the work from the LEEDR project: a recently completed, multi-disciplinary study into demand reduction in UK homes. The question addressed is the extent to which HEMS and other ICT enabled 'smart' systems (referred to in this paper as HEMS/ICT) can influence energy reduction in real family homes.

Method

In order to understand the potential role of HEMS/ICT in facilitating energy reduction in the home, a three stage approach was adopted:

1. carry out detailed monitoring in typical, mid-sized, UK family dwellings;
2. from literature, develop models of the impact of a set of common reduction measures;
3. review which reduction measures might be enabled/facilitated by HEMS/ICT; and then,
4. calculate the aggregate impact of these measures using consumption data and models.

Description of the homes

The study is focused on 11 family households in the Midlands region of the UK which are all owner-occupied. The construction year of the buildings ranged from 1900 to 2000, with most houses being constructed in the 1950s and 1960s. All except one have cavity walls and most had undergone some degree of insulation retrofit and installation of double glazing. The homes where a mix of detached and semi-detached buildings with one mid-terrace. A number of these have been extended with conservatories and/or masonry extensions and were generally 3-4 bedrooms, although a couple of the buildings were larger than this. The householders varied in terms of education, income and environmental awareness. Family sizes ranged from single-parent households with two family members to three-generation households with seven occupants. All homes had central heating; mostly driven through a combi-boiler that supplied hot water. Several had a traditional hot water cylinder based system. The ages of the heating systems varied from 1 to 2 years old up to 10 years old.

These dwellings are quite typical of a great many homes in the UK. The average combined gas and electricity consumption for homes of this type in the UK is about 20MWh/year, of which 17MWh/year is gas since the majority of space heating and hot water provision is delivered through gas-fired boilers. The homes studied here on average, consumed 13% more gas and 79% more electricity than the UK national average, although the range in the sample was from about 20% less, to over twice the national average. The variability in consumption is typical. The slightly higher average consumption is likely to be because the sample does not contain lower income households and most homes were occupied during weekdays to some degree.

Monitoring

Monitoring was undertaken continuously for 2 years and included: mains gas consumption; mains electricity consumption; monitoring of sub-circuits and appliances within the building; temperatures around the home and outside; activity within rooms through PIR (Passive Infrared) devices; some window opening activity; and hot water consumption. Measurements were made using a combination of the AlertMe system[1], a bespoke high resolution gas measurement system and hot water measurement devices that comprised of temperature measurements and an in-line flow meter (See [13] for more details).

Electrical measurements were sampled every minute, PIR and window opening devices were also at minute resolution, temperatures were measured every two minutes and gas and hot water every second. The data was rationalised to 1 minute samples to make data processing more straight forward. An average of 50 measurement channels per dwelling were made, the data was

[1] In March 2015, AlertMe was acquired by British Gas.

filtered and unreliable data removed. For the analysis reported here, a check was made to ensure that all necessary measurements were available on a daily basis throughout the monitoring period, rejecting those days where there was missing data. From these available days, a typical set of days was derived for each month of the year, and the analysis performed on these 'typical days', scaling up the results to provide annual reductions. In this way only complete data is used in the analysis, while capturing seasonal effects: outdoor air temperature in particular.

Modelling energy reduction

A review of energy reduction strategies was carried out in the literature. The main published opportunities for domestic carbon emissions reduction used in this work can be found in: more efficient heating and electric production, more efficient supply [14, 15, 16, 17, 18, 19, 20], retrofit and sealing of the building stock [21, 22, 16, 23], improved heating systems technology [24], more advanced heating and home controls [8, 25, 26]; greener lifestyle, occupancy and user choice [27, 28, 23, 29, 5, 30, 31, 32]; enhanced appliances and lighting technology [27, 33, 34]; and the application of ventilation control systems [35].

A subset of possible reductions affecting energy consumption was selected on the basis of the applicability to the homes in the study and the ability to model the impact on energy reduction based on the detailed monitoring data. 14 reduction measures were modelled and are listed in Table 1. These breakdown into 3 broad categories:

Lifestyle: these do not necessarily cost anything, but require the user to accept a lower level of comfort and convenience than they are used to; reductions in convenience include the user having to undertake additional activities in order to reduce energy demand.

Replacement: items that require small to moderate investment, but are not particularly disruptive, such as replacing an old appliance;

Retrofit: major undertakings that usually affect the building fabric or heat production (i.e. the boiler) that imply a significant cost and undertaking.

The approach taken here, was to consider a plausible range of reduction measures to provide a context for the role of HEMS/ICT in achieving expected reductions as we move towards 2050. Of the measures given in Table 1, six benefit from further explanation:

One fridge freezer: applied only in those households with more than one fridge/freezer, i.e. the reduction would be achieved if only one fridge and one freezer OR one fridge-freezer is used. This measure is considered a lifestyle change because it can affect the family routines for shopping and storing food.

Heating only when home: the data is used to estimate when householders are at home and hence when the heating could be switched off. The savings are therefore calculated by aggregating the energy that has been consumed at times where in the analysis we consider the householders to be absent.

In use heating: controlling the temperatures in individual rooms based on their use and occupancy has been estimated by analysing the reduction in energy that would be achieved if the occupants were to heat the whole house for only one hour in the morning, the living room for the whole evening and to heat only one specific room if someone is at home during the day. The temperatures in the 'unused' rooms are maintained to at least 16℃.

Table 1: Energy reduction measures at a glance.

Type	**Affects**	**Measure**
Lifestyle	Reduced comfort & convenience	One fridge-freezer
		Minimal standby loads
		No tumble drying
		Heating only when home
		In use heating
		No heating over 15℃
		Heating to 17℃
		Minimal ventilation
Replacement	Cooking appliances	Replace cooking appliances
	Cold appliances	Replace fridge-freezer
	Laundry appliances	Replace laundry appliances
	Digital media devices	Replace media equipment
	Doors	Insulated doors
	Lighting	Replace bulbs
Retrofit	Loft	Loft insulation
	Walls	Wall insulation
	Floor	Floor insulation
	Windows	Triple glazing
	All building	Sealing
	Heating system	New boiler

Heating to 17℃ : setting the thermostat to 17℃ , hence the energy reduction is based on heating the home to a maximum of 17℃ . The energy required to heat the building to more than 17℃ (as monitored in practice) is therefore considered to be the reduction potential.

No heating over 15℃ : minimising the duration of heating the house. When the outside air temperature is at over 15℃ , it is assumed that the internal temperature will be around 17℃ so there is no need for space heating. In the UK the internal heat gains from people and appliances tend to be sufficient to raise the internal temperature a couple of degrees.

Ventilation: householders only ventilate the home to the minimum level required to satisfy the physiological needs of the occupants (i.e. to be able to breath and to remove CO_2 and other contaminants). The method estimates the heat lost through ventilation during the monitored period and this is converted to a ventilation rate. This rate is compared to the theoretical minimum and the energy required to heat the air over this level is considered to be the reduction potential.

Sealing: the sealing of gaps and cracks in the structure to avoid infiltration of cold air. Infiltration is the outside air that finds it way into the building that is not intentional - i.e. through the opening of windows. It's uncontrollable and hence by sealing cracks this is minimised. In the calculations the energy saving is based on the results from published field studies [36].

All the measures in Table 1 were modelled and used to filter the monitoring data to represent each case resulting in two sets of data, one baseline and one with the reduction measures applied. Using the monitored gas and electricity consumption data from the baseline model, the actual total annual energy consumption can be estimated. The filtered data describing the home with reduction measures was then run through a model to calculate the resultant energy consumption, by estimating the gas and electricity use. The baseline and the filtered results were compared and the procedure repeated for any combination of reduction measures. The principles of the modelling approach can be found in [37].

This approach is necessary because reductions do not necessarily aggregate in series, particularly in relation to heating and hence they must be treated simultaneously. For example, the reduction in the volume of gas used after changing the boiler for a more efficient one and setting lower temperatures in the home are interdependent. The published impact on energy consumption from trials have been used to generate realistic estimates of the reductions that might be expected. Models are also based on published values for new materials (U-value, for example) and systems (e.g. power consumption of a new device) where possible.

To give some scale to the potential reductions, the total reductions were compared with a notional 2050 reductions target. The reduction target is based on published values from the Energy Saving Trust [38] and is the consumption that achieves an 80% reduction in CO_2 emissions, based on the 1990 national average performance for a three-bedroom, semi-detached property, normalised by the average gross internal floor area.

An 80% reduction from these figures led to a primary energy target of 115kWh/m^2/year and an emissions target of 17kgCO_2 /m^2/year [38]. This figure was also comparable to those published by DECC [39], which reported national figures for each 2050 scenario.

Results and discussion

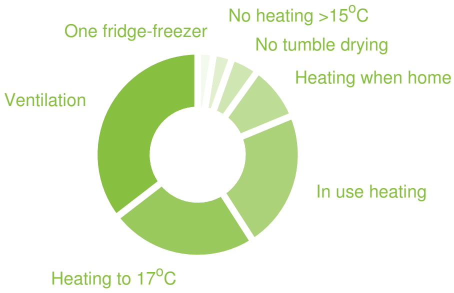
The average reductions in consumption across the studied homes are presented in Figure 1. The plots a - c (green, red and blue) show the proportional reduction in energy consumption from each reduction measure if applied on its own in each of the three categories: Lifestyle, Replacement and Retrofit: the relative weight of impact reductions in that group is indicated by the ring thickness. Reductions less than 1% were not shown in the Lifestyle and Retrofit categories (green and blue).

Figure 1d brings together the total reduction potential if all measures were applied: the circumference represents the annual energy consumption of the (sample average) household today, i.e. 100%. Reductions are shown in a coloured bar rotating in a clockwise fashion, hence the 'white' section between 7 o'clock and 12 o'clock represents the minimum energy consumption that could be expected after applying all the reduction measures. The ocre outer ring indicates the anticipated reduction required in order to achieve the 2050 reduction targets.

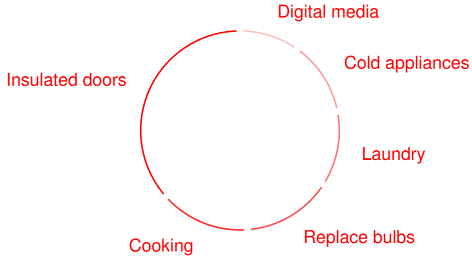
Figure 1 depicts average results from the sample, across the 11 homes. The total energy reduction potential ranged between between 50% and 70%. It was, however, the lifestyle category where the reductions *varied* the most. An average of 33% reductions could be made through implementing all the lifestyle measures, which is very similar to the total available through implementation of the retrofit measures. However the level of reductions varied $\pm$15%, three times that of retrofit measures, suggesting that how we choose to live/use energy in homes does vary considerably between families.

Although the prognoses suggested by the results are optimistic, they are in-line with observations published in other studies. For example: lifestyle reductions are close to those reported on a study which published possible savings of 39%, considering inefficient use of space heating and appliances [25]; a study looking at reductions from retrofit measures reported a possible CO_2 reduction between 50% and 80% compared with 1990 average levels [38]; and studies looking at possible savings from electric appliances via feedback and information such as more with informative bills, direct, immediate feedback and smart meters, have shown potential for savings between 5% and 20% [28].

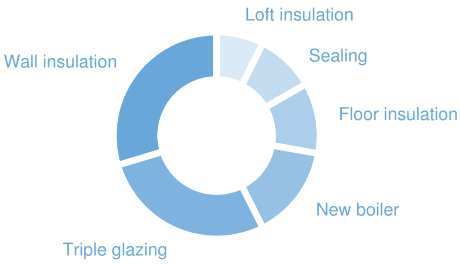
What is also evident from Figure 1, however is that retrofitting measures and replacement combined cannot satisfy the proposed reduction target, meaning that some reduction in comfort and convenience will almost certainly play a role in achieving the reduction targets in the future. This is exacerbated when consideration is given to the application of external wall insulation included



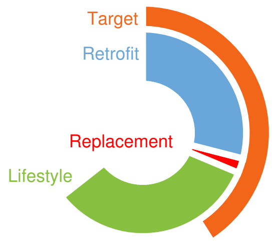
(a) Reductions though changes in lifestyle.



(b) Reductions through replacement.



(c) Reductions through retrofit.



(d) Total reductions against 2050 target.

Figure 1: Breakdown of potential reductions based on the average LEEDR home today.

in the retrofit category which is not only expensive, but also has significant impact on the aesthetics of the property and the disruption of the building works which can be messy and dirty for families to live in; hence its ready application (in the UK at least) is questionable [40].

What the analysis does suggest, however, is that there is the balance point between capital investment and some acceptance of a reduction to comfort and convenience, which the authors term the 'Reduction Effort Balance' (REB). The REB is an approach that can be evaluated for each home and is useful in visualising the reduction options available to a specific home. HEMS/ICT can potentially shift the balance helping home owners mitigate the inconvenience that the lifestyle reduction measures entail.

Impact of HEMS/ICT on reduction potential

Basic HEMS enabled by ICT provide householders with feedback on their electricity via an in-home user interface ([12], for example). More advanced HEMS provide individual appliance monitoring and/or remote control over heating. Solutions that also provide zonal heating control are also becoming commercially available. Control automation can result in the reduction of wasted energy that would practically impossible otherwise: optimal starting of heating in response to patterns of occupancy is one such example. ICT potentially gives the user a more intuitive means of accessing critical set-points and parameters, and so makes actioning desired changes more achievable.

Observations from this study suggested that most of the lifestyle reductions were actually achievable without the need for automation or HEMS/ICT over and above traditional domestic control methods. Most, however, require ongoing commitment from householders. The opportunities for HEMS/ICT falls within the lifestyle reduction measures where automation and control can empower and encourage householders to make changes to the way they consume energy and provide convenience. All of the lifestyle reductions listed earlier apart from ‘One fridge-freezer’ and minimizing use of the tumble dryer can be enabled through HEMS/ICT using technological solutions that are already commercially available or in the process of being commercialised.

Reduction in inconvenience can be minimised through reducing the need for householders to adopt new behaviors (perhaps requiring the breaking of long established habits) as well as enhancing convenience by shifting responsibility for decision making from the household to the smart system. For example HEMS/ICT could be configured to ‘power down’ any unnecessary stand by loads every night from one bedside switch. Similarly although reductions to thermal comfort can be somewhat minimised though everyday behavior change (e.g. putting a sweater on in response to turning down the heating) HEMS/ICT can also facilitate energy demand reduction whilst helping households maintain desired levels of comfort by for example: responding to a householders preference for fresh air by automatically switching off any radiators in the proximity of the opened window or door [41]; providing convenient but short term boosting of heating via for instance a smartphone app and even encourage adaptation of thermal comfort preferences overtime though gradual reduction of set points which will faciliate acclimatization [42].

The reduction analysis presented suggests that HEMS/ICT could potentially provide savings similar to those likely to be achieved through expensive and disruptive retrofit measures and also have a higher impact on demand reduction than the replacement of appliances. In an attempt to evaluate what proportion of the total reduction potential that might be enabled by HEMS/ICT, the lifestyle categories were revisited in order to select those measures where it might be reasonable to expect a strong role for HEMS/ICT. Table 2 describes how HEMS/ICT might affect the implementation of the lifestyle reduction measures, and whether these are practically achievable without HEMS/ICT.

Table 2: HEMS/ICT energy reduction measures.

Description	**HEMS/ICT relationship**
No standby loads	Appliances can be turned off manually, however, remote access to switching or implementing algorithms that learn behavior using ICT increases the likelihood of unused appliances being turned off, hence reducing unwanted energy consumption.
Heating only when home	Similar to the above comment, can be affected with manual control, but it much more likely to be effectively implemented with a degree of autonomous control automation.
In use heating	Zonal control of rooms is currently practically difficult to implement in rooms except those that are ‘always’ unoccupied and so ICT enabled control has an obvious advantage.
No heating over 15°C	Automated control scheduling is practically impossible with existing systems. Future ICT enabled systems could automate response to key variables such as outdoor air temperature.
Ventilation	In building that use windows for ventilation (as opposed to HVAC systems) manual control is still the most likely means of operation. However, ICT could enable monitoring of windows controlling or advising when they should be closed, for example when the house is empty or heating is on etc.

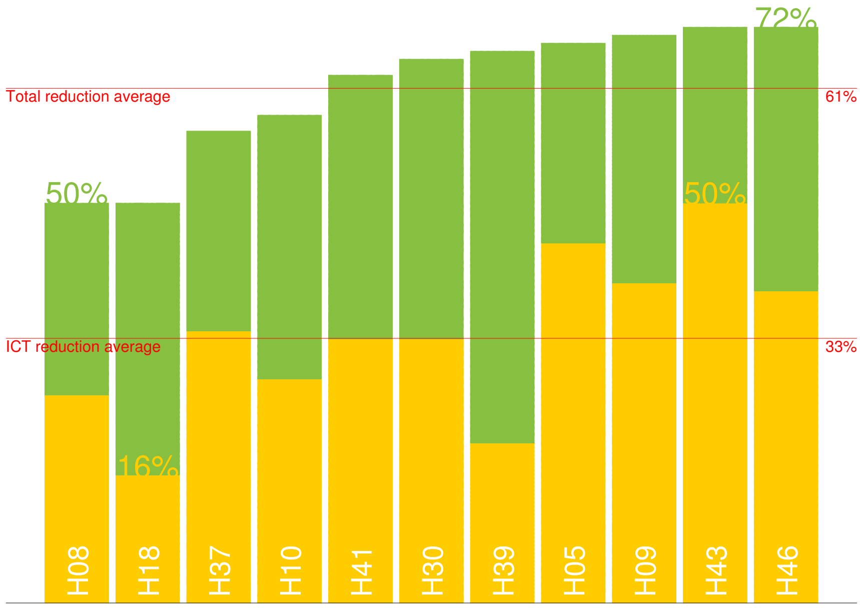


Figure 2: Reductions as a percentage of total energy consumption through ICT (yellow) and through all other measures (green).

Figure 2 compares the reductions that might be achieved through HEMS/ICT, as listed in Table 2. The total reduction potential from the initial investigation (Figure 1) for the 11 homes (which are coded in the horizontal axis of Figure 2) is depicted. The yellow portion of each bar describes the reduction associated with the HEMS/ICT interventions. Average values for the group are shown in red. An average of 61% reduction in current energy consumption is possible across the group, and of that 33% might be enabled, or enhanced by the application of HEMS/ICT systems.

Conclusions

HEMS/ICT is seen as being an important component in realising the energy and CO_2 reduction measures in the UK. This work attempted to quantify the potential opportunities for HEMS/ICT in terms of energy demand reduction in typical, mid-sized family homes in the UK. The analysis was based on detailed longitudinal monitoring and modelling the effects of common energy reduction measures. A number of observations were made:

The impact of lifestyle varies between homes: An average of a 33% reduction could be made through implementing changes in lifestyle, similar to that offered by retrofit measures, but the level of reductions varied $\pm$15%, three times that of the variation in retrofit.

Reduction Effort Balance: The concept was introduced here for the first time to describe the tipping point between benefits gained through capital investment over those gained through the acceptance of lower levels of comfort and convenience.

Opportunities of HEMS/ICT exist over 50% of potential reductions: the prognosis for the usefulness of existing systems and new innovations is strong if HEMS/ICT can help mitigate the loss of comfort and inconvenience that comes with implementing lifestyle changes.

Although the analysis takes an optimistic view of the impact of potential reduction measures, the analysis indicates that the suggested 2050 reduction target contributions are achievable for the type of home studied here. Although the sample studied is small, these homes are very typical of those found throughout the UK, and the authors were encouraged by the results. However, it was also noted that while some homes would find it relatively easy to achieve targets, others would find it very difficult, either due to having already a retrofitted house which still consumes high levels of gas or due to having already applied some lifestyle measures (such as lower room temperatures) but still be over target levels.

Retrofitting alone, it seems, will not generate sufficient reductions in all cases and hence it is extremely likely that some degree of lifestyle change (reduction in comfort and convenience) will be required in the future. It's worth noting that in the study here, both the application of external wall insulation and consideration of ventilation are sensitive components in the model. The application of external wall insulation in the UK it's not an attractive solution currently and without this additional insulation, there is further pressure to decrease comfort and convenience. In addition, minimising ventilation plays a key role in lifestyle reductions, but the actual impact is difficult to quantify, particularly in older properties that maybe damper and require greater ventilation, apart from the challenges associated with drying washing during the winter months and the resulting requirement for increased ventilation.

What the study has demonstrated is that although significant reductions are within reach, the application of HEMS/ICT can play an important role, and this will be against a changing landscape depending on the penetration of retrofit technologies and practicable levels of ventilation in the home.

Acknowledgments

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USmartConsumer: real-time smart meter feedback to kick-start consumer interest

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Abstract

In line with EU legislation, considerations for large-scale smart meter rollouts take place in a growing number of Member States. However, it's hypothesized success for energy savings should not be taken for granted. Smart meters can only contribute to energy efficiency, if they come publicly accepted and in line with engaging and empowering smart metering services. To help meeting these preconditions, the EU-networking and dissemination project USmartConsumer encourages both European market players and households to benefit from smart metering, among other things by promoting scientific evidence and consumer interest.

The latest scientific evidence comes from the Netherlands. A large and multiple consumer behavior pilot program, one of the largest scientific smart metering trials conducted worldwide to date, recently added new evidence to the smart meter energy savings potential. As seen in similar trial programs in the UK and Ireland, smart meters in combination with direct feedback can lead to considerable and persistent household energy reductions. In-home displays appear to be a crucial 'stepping stone' to kick-start consumer interest and engagement in accessing energy information, especially amongst less committed or experienced consumers. Sophisticated web-based services on PC, tablet and smart phone are potentially more powerful to help reduce energy demand, but in practice more so with already committed and technology minded subsets of the population. Therefore, opt-in websites or apps should not be considered as the contemporary substitute for in-home displays, but rather as a complementary option. This paper elaborates on the outcomes of the Dutch pilot series and reflects on the readiness of the market in the Netherlands to kick-start consumer interest.

Introduction

Backed by rising energy demands and fears over security of supply and climate change, smart metering is rapidly gaining momentum across the world. Europe is expected to become a world leader of this development, thanks to the European Services Directive (2006), Third Energy Package (2009) and Energy Efficiency Directive (2012). The Energy Services Directive laid the foundation for a European wide legislation for smart metering, by requiring individual energy meters and standards for frequent and understandable energy bills. The Third Energy Package accelerated the penetration of smart electricity metering in EU by setting a target of at least 80% of all households to have a smart meter by 2020, given a positive economic assessment. Last but not least, the present Energy Efficiency Directive connects the smart meters directly to dynamic pricing and improved feedback programs and empowers smart meter and consumer feedback regulation.

Although serious considerations for large-scale smart meter rollouts take place in a growing number of Member States, public support and hypothesized energy savings should not be taken for granted however. Smart meters are generally hypothesized to contribute to increasing consumer involvement and enable effective household energy savings, if smart meters become publicly accepted and be combined with empowering energy management services. This paper aims to contribute to the already existing evidence based literature to back this statement up.

To help Member States meet these preconditions, the USmartConsumer project was initiated by several European energy agencies, market players and consumer associations.[1] The project's aim is to contribute to public support for smart meters and beneficial market conditions for market players in

[1] Project funded by Intelligent Energy Europe (IEE 13-590) with participants from Austria, Finland, Germany, Italy, Netherlands, Poland, Spain, United Kingdom.

the Member States. This is mainly done through market analysis updates of smart metering services developments in the EU, initiating promotional consumer engagement activities in the partner's Member States and -last but not least- dissemination of new evidence in the smart meters potential to save energy, delivered by scientific based consumer behaviour trials in Europe.

Being part of the USmartConsumer dissemination activities, this paper elaborates on the research evidence for smart metering based energy saving potentials, coming from the Netherlands. Following the United Kingdom and Ireland, the Netherlands are the third Member State in which realistic consumer behaviour smart metering trials in combination with multiple innovative energy management tools across the country have been undertaken. On request of the government, the Netherlands Enterprise Agency in cooperation with some of the larger network operators developed a monitoring program based on both literature reviews of previous consumer behaviour experiments with smart meters as well as new pilots with various smart meter feedback interventions between 2011 and 2014, all primarily directed at reducing domestic energy consumption. Involving thousands of households, the Dutch pilots are among the largest scientific smart metering research trials to test consumer responses to different forms of feedback instruments, conducted worldwide to date.

This paper starts with a brief introduction on smart metering and a short overview of the legal rollout situation in the Netherlands. The main section of the paper collates and reviews the outcomes of the previous experiments as well as the latest pilot findings in the Netherlands in order to build on the wider international literature to identify the interventions that have proved most effective in reducing consumption. The paper concludes with a brief overview of the key lessons learned on how such interventions can best be delivered to the European consumer.

By elaborating on the recent experiences in the Netherlands, the USmartConsumer project partners hope to provide practical lessons to stakeholders in other Member States who are still searching for evidence about the smart metering energy savings potentials. Additionally, the policy approach adopted in the Netherlands to learn together with relevant stakeholders about end-user engagement and subsequently arrive at a better rollout strategy and more promising prospects for energy savings, could inspire other Member States to develop regulatory frameworks that are more likely to contribute to consumer satisfaction and energy efficiency. The monitoring program in the Netherlands provided relevant input for the Government to underpin the Ministerial Decree for the large-scale roll-out of smart meters in March 2014.

Smart metering rollout in the Netherlands

In line with European legislation, the Dutch Government and Parliament agreed in 2011 to start a phased rollout of new electricity and gas meters for consumers and small businesses.[2] These energy meters, widely known as smart meters, are the next generation of meters to replace existing electro-mechanical meters. Smart meters can potentially offer new benefits, both for the individual electricity and gas consumer and for the network operators and energy suppliers. For network operators, automated recording of actual energy usage over short intervals and automated communicating of metering data to the network operator will facilitate more cost-efficient network operations such as eliminating the need for manual meter readings. Electricity suppliers will be able to introduce new pricing arrangements for consumers and support more efficient use of energy (i.e. time-of-use tariffs).

But the smart meter also offers potential advantages directly to the consumer.[3] Smart meters can put an end to estimated billing (people will only be billed for the energy they actually use) and allow easier switching of supplier to get the best deals. However, the most immediate consumer benefit of the smart meter is the ability to receive more frequent and more detailed feedback information on how much energy is being used. With regards to the more frequent feedback information, the smart meter offers basicly three options to the Dutch consumer.

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[2] In 2009, the so-called Energy Package was established at the European level, which stated, amongst other things, that under conditions in 2020, at least 80 % of households must have fitted a smart meter.

[3] Where this paper refers to households or consumers, it also refers to the small business consumer throughout.

Firstly, Dutch consumers with a smart meter will receive next to their annual bill, several interim consumption and cost statements from the energy supplier, hereinafter referred to as energy usage statements. The energy usage statement is established in Dutch legislation and subject to minimal requirements, in line with European legislation (Ministerial Decree Energy Usage and Cost Statement, 2011). This statement must provide insight into the actual consumption at actual energy prices and must compare this to previous consumption periods and to comparable end users. Energy suppliers are obliged by Dutch law to offer the energy usage statements at least 6 times a year to every customer with a smart meter. The bi-monthly statement must be delivered actively, either by regular mail or as a PDF attachment to an email. It is not sufficient to merely provide the report passively on the supplier's website.

Secondly, if so desired by the consumer, the smart metering data can also be sent on a daily basis to the energy supplier - or another smart metering service provider - for additional and more detailed energy consumption analysis over the previous days, weeks and months in combination with tailored energy reduction advices.

Finally, consumers will be able to receive energy consumption information directly and in (near) real-time by connecting a wireless transmitter or 'bridge' to the so-called P1-port on the smart meter for an in-home display or online application on the consumers own PC, laptop, tablet or smart phone.[4] Providing customers with products and services to better monitor and manage energy consumption, is by law considered to be a market responsibility in the first place. To support the market development for real-time smart metering services, functional requirements for the standard smart meter have been established in legislation.[5] Additionally, the grid operators have established technical specifications for the P1-port in a so-called companion standard.[6] Dutch standardised smart meters are thus equally designed to facilitate energy efficiency by empowering consumers with more detailed, accurate and timely information regarding their energy consumption and costs. As a consequence, real-time monitoring products and services are now emerging on the Dutch market.

Legal considerations for smart metering rollout

The Dutch Government's objective is to have standardised smart electricity and gas meters offered to all residential and small business customers and installed by at least 80% of the population by the end of 2020 (Ministerial Decree Large-scale Roll-Out Smart Meters, 2014). Residential and small business customers in the Netherlands are not obliged to accept a smart meter. Customers who object to the installation of the smart meter can either have the communication of the smart meter deactivated, or even refuse the installation of the smart meter. If the standard smart meter is administratively deactivated, the smart meter will actually function like a traditional meter. In case of refusal, the old electricity meter (and gas meter) will remain in place, and the meter reading cannot be done remotely. In case of acceptance, the consumer can choose to have the smart meter read remotely at all times or limited to specific situations appointed by law (annual bill, bi-monthly energy usage statements, when switching supplier or moving house).

It was agreed in the Dutch Parliament in 2011 to introduce standardised smart meters according to a two-phase rollout-approach, to begin on a small scale in 2012 untill 2014.[7] During this initial rollout period, the smart meter was only installed in the event of new construction and large-scale

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[4] The traditional mechanical and digital pulse meters also provide the option for real-time information on household energy consumption. These older generation meters use optical 'readers' which can also be attached to the electricity meter and possibly also to the gas meter, instead of a special connection option (also called a P1 port). However, such a system is rather prone to errors compared to when smart meters are used.

[5] In January 2012, the Ministerial Decree on remote-readable metering devices (hereinafter referred to as: the Decree Meter Requirements [*Besluit Metereisen*]), came into force. This Decree placed minimum requirements on the smart meter, by establishing the functionalities that are deemed important from a social perspective and in view of privacy and security.

[6] These requirements are included in the so-called Dutch Smart Metering System Requirements (DSMR)

[7] When reference is made to the smart meter, it also means the gas meter, in addition to the electricity meter, throughout. With the installation of the new electricity meter, the gas meter – if present – is also replaced and then connected to the new electricity meter (in a wired or wireless fashion). The smart meter thus applies, in general, to both electricity and gas.

renovations and in the case of malfunctioning existing meters. The consumer was not charged for this type of installation/ replacement.[8] The purpose of this phased rollout approach was to meet European legislation and to gain crucial rollout experiences and information on consumer responses to provide input for the parliamentary decision on the second phase, the large-scale rollout between 2015 and 2020.

Among the imperatives to support a parliamentary decision on the large scale rollout of standardised smart meters in the Netherlands, was the need for a scientific verification of the presumed residential energy savings potentials as quantified in the national Cost-Benefit Analysis (CBA) for the introduction of smart meters, executed in 2010 (Van Gerwen et al., 2010). In this CBA it was estimated that the smart meter, in combination with sophisticated forms of feedback interventions, can potentially result in average savings of 6.4 % for electricity and 5.1 % for gas. Energy saving is therefore expected to be among the most important benefits for society, resulting from the introduction of smart meters in the Netherlands.[9]

To substantiate this, the Minister of Economic Affairs committed to the House of Representatives to provide more insight from new pilots in the true savings from the smart meter in combination with various feedback systems during the small-scale rollout. The coordination of this pilot program was assigned to the Netherlands Enterprise Agency.[10]

The following sections review the overall findings from the national research executed to date in the Netherlands to identify the interventions that prove most effective in reducing consumption from smart metering services. The first section presents a review of the existing research literature related to earlier smart metering consumer behaviour experiments in the Netherlands. After that the pilots conducted as part of the small-scale rollout), executed by the Dutch network operators Liander and Stedin, will be reviewed in more detail. In reading these sections, it should however be noted from a general scientific point of view that experiments and pilots often tend to relate to relatively small populations, with a chance of self-selection amongst participants who know they are being studied, also named the Hawthorne effect (Darby, 2006). The results of this pilot program should therefore be seen as indicative, rather than representative for the entire Dutch population.

Literature review of earlier Dutch smart metering experiments

In the Netherlands, approximately five studies have been conducted to better understand how consumers react to improved feedback from smart meters, prior to the small-scale rollout. These studies are briefly explained below.

Energy supplier Oxxio was the first, in 2008, to conduct trial research on the effectiveness of savings achieved with the smart meter, in combination with non-realtime (also called indirect) feedback through an online self-service platform (Jonkers et al., 2011). This supplier based web service, called MijnOxxio, provided customers with additional insight into their (historical) energy and gas consumption, as well as information on tariffs and costs, through a personal web page on their own PC / laptop. The Universities of Amsterdam and Maastricht conducted research amongst 2,513 of Oxxio's clients for a period of two years. The researchers found that clients who used the web application, consumed on average 1.5 % less electricity and 1.8 % less gas compared to other Oxxio clients with a smart meter, but without using the website.[11] Three-quarters of the examined group still

[8] Smart meters replacements on the consumer's request took place in return for a reasonable network operator fee.

[9] The savings referred to in the KEMA report are based on an expert assessment of a realistic potential based on literature studies. The KEMA report herewith states emphatically that it does not (merely) involve the introduction of a smart metering infrastructure or display, but that use of this metering infrastructure and the method of feedback also have a major influence.

[10] The Netherlands Enterprise Agency succeeded the NL Agency as the implementing body for policy regarding sustainability, innovation, and international business and cooperation for the Dutch national government.

[11] A comparison to households without a smart meter, as a control group, was not included in this study, which means that statements could not be made in this respect.

visited their personal web page after a year to obtain insight into their in-home changes in consumption.[12]

In 2009, energy supplier Nuon and Eindhoven University of Technology conducted a small trial to investigate the development of consumption behaviour amongst consumers with a smart meter and a real-time in-home energy display (UC-Partners et al., 2009). Because of the high production costs for the displays, the trial involved no more than 40 households with a smart meter, where one half received a real-time energy display and the other half did not. Both groups were equal in terms of composition, domestic environment and environmental motivation – after scientific selection – and were given the same instructions and recommendations for achieving savings.[13] After four months, the researchers found that a considerably higher portion of participants with a display appeared to be able to save energy, compared to households without a display.[14] The display group also succeeded in saving considerably more energy (average of 9 % for electricity and 14 % for gas) than the group without a display (3 % for electricity and 2 % for gas, respectively). To conclude, the display group expressed more positive feelings about the test and complained less about the (time) effort. After some time, the participants started to understand their own consumption patterns better and felt less need for daily consulting of the system. The participants without the display reported less positive experiences, and considered their participation to be more of a hassle. The researchers concluded that a real-time display can contribute significantly to willingness to reduce energy consumption.

In 2010, the previous experiment was continued on a ten times larger scale, under the name West Orange, in the context of Amsterdam Smart City (Noort & Van Ossenbrugge, 2011). Amongst approximately 400 households – mostly home owners – researchers from the University of Amsterdam again saw an increased energy awareness and development of energy-saving behaviour. According to the researchers, the in-home display ignited a pre-existing need amongst consumers to monitor energy consumption as well as the effects of savings measures. This resulted in a significant reduction in energy consumption, 4.5 % for electricity and 4.6 % for gas, which was not observed in the control group.[15] Moreover, the researchers stated that these savings only represent the lower limit, because not all displays functioned to the best possible extent. Another finding was that the savings were mostly the result of simple behavioural changes that required little or no investment of time or money (low cost quick-win). Longer-term investments aimed at energy savings, were not or hardly taken into consideration.[16] Despite the prototype technology and aesthetics of the display, the majority of participants (58 %) were interested to have such a device at their disposal.

Research by Delft University of Technology, on the effectiveness of in-home displays between 2008 and 2012, highlighted the relevance of habit formation (routine use) with the feedback system for persistent savings in the longer term (Van Dam, 2013). In this experiment, researchers installed a real-time electricity monitor which provided information on actual consumption, daily consumption and a comparison with a savings target, at 54 households (with a traditional meter).[17] After four months, the households were split into a group of 28 households that returned their display (in exchange for € 25) and a group of 26 households that wanted to keep the display. After 11 months, it became evident

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[12] The frequency, with which the personal area of the website was visited, is not known.

[13] The participants were scientifically selected from a large group of 50,000 households and were divided into two groups by way of invitation (1,000 households) and questionnaires (approximately 200 households), equally on the basis of environmental motivation and behaviour.

[14] In the display group, 81 % achieved savings for electricity and 100 % for gas. In the group without a display, 47 % succeeded in achieving savings for electricity and 65 % in achieving savings for gas.

[15] The control group consisted of approximately 3,000 households, drawn randomly from Nuon's client base in the Amsterdam region.

[16] This observation may also be due to the fact that the majority of the participants reside in homes that are better insulated (wall insulation and double glazing, in particular).

[17] It involved an electricity display named Wattcher, manufactured by Innovaders in Amsterdam. All participants were also offered to use an online advisory and registration system for processing of the meter readings that were taken individually. Most participants had a traditional electricity meter.

that the savings achieved in both groups, in the first four months, declined.[18] With the households that returned the display, the previous savings of 3.9 % dropped to a negative savings of -1.0 % (a consumption increase over the original level of consumption). With the display group, the savings also decreased, depending on the extent to which the display was used routinely. Irregular users of the display (12 households), experienced a 6.3 % level of savings after 4 months, dropping to 1.7 % after 15 months. The users who kept to their daily routine of consulting the display (most common use was the 'bed-time' base level check) also experienced a reduction in savings, but maintained significant savings levels of 7.8 % after 15 months. The survey pointed out that the magnitude of savings depended on the persistence and intensity of households' use of the feedback device. It was also concluded that an energy display is only an effective trigger in the long term amongst consumers who are more receptive to energy savings (Van Dam, 2010). Furthermore it is emphasised that the feedback should not be limited to a single user alone as is often the case with (mobile) web based services. The importance of family dynamics, as a stimulus for the acceptance and use of home-energy management systems, should not be underestimated (Van Dam, 2013). An energy display at a convenient location in the home, which is amenable to all members of the household, was found by this study to trigger family discussions and an increased chance of acceptance and persistent use of the energy display.

Results of the Dutch small-scale rollout pilot program

The previous smart metering experiments, described above, did not fully represent the current range of feedback methods and also do not relate to the consumer behaviour responses from all population groups. For example, they did not include sophisticated web based services on modern mobile media such as tablets and smart phones. In addition, most participants in the previous experiments tended to be generally home-owners with higher incomes and / or education levels and more interested in energy savings. Consumers from lower income groups, were generally not represented in these studies. In order to draw conclusions on modern media and fuel poor consumers as well, two pilots were conducted during the small-scale rollout phase by the network operators. The main results of both pilots are reviewed below.

Energy management app for smartphones and tablets

In 2014 grid operator Liander published the results of a 12-month consumer behaviour pilot, using a smart meter and a feedback app for smart phones, named 'Energy Warriors" (Liander, 2014). The energy management app provided live data on energy consumption in energy-units and in costs for electricity and gas. The app also enabled comparison of the household's consumption against previous periods or with a reference group of households (benchmarking). Finally, the app provided the option to set a savings target, to continue the incentive for consumers to lower their energy consumption.

The field trial started in June 2012, and included approximately 500 residents in the city of Arnhem, mainly home owners with a higher income, education and environmental motivation. A quantitative consumption change measurement based on meter readings amongst approximately 330 participants, showed an average reduction in consumption of 3 % for electricity and an average of 4 % for gas over a year, compared to the forecast consumption for this group. The forecast consumption of electricity and gas was based on quantitative research through a historical trend line analysis, where this consumption is compared to the smart meter measurements. The results of the effects measurement were checked by the independent research agency IVAM, using a multiple regression analysis (MRA) and the non-active participants as a control group check.[19]

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[18] The evolution of consumption for the different groups is based on the meter readings provided by the participants, divided over 5 research periods. Since many errors were made during this process, the study of the effects was eventually conducted with 54 of the original 264 participants.

[19] IVAM is an independent research and consultancy organisation in the field of sustainability and is specialised in statistic scientific research, amongst other things; originating from the Interfaculty Department of Environmental Science [Interfacultaire Vakgroep Milieukunde] at the University of Amsterdam.

The accompanying consumer experience survey, covering approximately 160 participants, found that the app had a high effect on raising energy awareness, but a relatively low effect on the energy-saving behaviour. A mere 18 % drew a connection between the measures that were taken and the provided app, 35 % did not see any connection, and 47 % only saw a partial connection. According to the researchers, this could be due to the already higher environmental motivation amongst most participants, which meant that many measures were already taken in the past. Also, the frequency of using the app dropped substantially during the pilot period: by the end of the pilot period approximately two-thirds of the respondents used the direct feedback app only once a month or even less frequently. As seen in the other direct feedback pilots, most energy saving measures had a low cost / quick-win character. Longer-term investments were less taken into consideration.

Energy dashboard for fuel poor consumers

Network operator Stedin, in cooperation with housing corporation Woonbron and the City of Rotterdam, published the results of another trial investigating the consumer responses to a smart meter in combination with a real-time energy dashboard among 140 households in the low rental segment (Stedin, 2014). This trial involved an in-home energy monitor for smart meters with a non-numerical dual fuel user interface, resembling a car dashboard. Users can obtain insight into changes in consumption at a glance, both in real time and for past periods (month and year) and can compare this information with a self-set savings target and/or previous consumption periods. This population group was targeted to build more understanding of how to best support the fuel poor during the smart meter roll-out.

Following a local information campaign, approximately 325 residents of rental homes in the Rotterdam residential area IJsselmonde, mostly insulated in a moderate to poor fashion, were invited for the pilot. The interest to participate in the pilot seemed high with this target group, which was previously thought of as difficult to motivate. Nearly half of the invited residents wished to participate in the pilot, and of these nearly 90 % completed the pilot, which lasted nine months.[20] Furthermore, a majority (60 %) of the participating households used the energy dashboard actively throughout the pilot and succeeded in achieving substantial energy savings; average of 5.6 % for electricity and 6.9 % for gas, compared to the multi-annual historical consumption data. However, more than half of the participating households achieved savings of more than 10 % on electricity and gas. Since roughly half of the participants developed a daily or weekly habit to use the energy dashboard which continued even after nine months, it appeared that many users experienced continuous reinforcement and continued to take up the challenge to consult the energy dashboard to persist in their energy savings.

Additional consumer research at the beginning and at the end of the pilot, which involved 75 % of the participants, reflected a high recognition for the PowerPlayer energy dashboard. Three-quarters of the respondents experienced the PowerPlayer display as a ‘missing link’ to activate consumer interest and engagement in in accessing energy information from smart metering. Most respondents highly appreciated the energy dashboard because the resemblance to a car dashboard for electricity (and a gas burner for natural gas) was well understood. Most participants also found the PowerPlayer easy to operate and that the display did not contain any superfluous functions.[21] This appreciation is even more evident from the fact that 70 % of respondents wanted to recommend the dashboard to others. As seen in other real-time feedback studies, most savings measures required little or no investment of time or money. The most frequently taken savings measures were turning down the thermostat, turning heat off in unused rooms, switching lights off in unused areas and unplugging chargeable devices from outlets, avoiding stand-by mode and also cutting down on showering time. Longer-term measures directed at energy savings were (expectedly) not or hardly taken into consideration.

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[20] Of the approximately 325 households that were approached, 142 households (45 %) participated in the pilot. Of the initial 142 participants, nearly 90 % (roughly 125 households) completed the pilot programme. In addition, approximately 75 % of the participating households (105 households) also contributed to the final survey.

[21] Some older participants felt that operation was still rather difficult. The older generation formed a relatively large part of the pilot participants (23 % of the participants were older than 70).

Finally, as already referred to in the consumption change evaluation, the frequency of use of the energy dashboard display did not see as great a decline over time as has been seen in some other trials. After nine months, more than half of the respondents still checked the energy dashboard every day to every week. The decline in the use of the display amongst the active users seemed to be the logical result of habituation, the learning effect and the 'running out' of (behavioural) quick-win measures. As consumption patterns continue to become more familiar to the end-user, the need for frequent display consulting and initiating behavioural measures becomes less. Then the emphasis turns from (daily to weekly) consumption monitoring and initiation of measures, to a (weekly to monthly) habit of consumption checking and consolidating of the lower consumption.

Evaluation of the Dutch smart metering experiments and small-scale pilot program

Even when taken into account the relatively small-scale nature of the experiments and pilots and the risk of self-selection and influencing through trialling, it appears that smart meters with sophisticated feedback, can have a significant impact on in-home energy consumption and to the savings to be achieved with it. The opportunities for savings look most promising in the case of real-time feedback. Even so, long-term success is not guaranteed: engagement and habit formation through continuous feedback reinforcement are also important for persistent savings. Only if the feedback instrument meets the practical user preferences and the functionality and data presentation (interface design) match with the consumer's interests and capability, persistent savings are more likely.

At the hardware level, this indicates that advanced web based applications on PC, tablet or smart phone will have a better chance of succeeding with already committed, technology-oriented and internet savvy consumers. For these consumers, comprehensive functional data analytics and multiple graphic presentation options, in combination with the ease of (mobile) multimedia devices, will offer the desired added value for habit formation to use the system. As seen in the study by Oxxio, many participants - customers with a predominantly higher education and environmental motivation - also visited the personal section of the website after a year, to keep detailed track of their in-home energy consumption progress.

On the other hand, advanced web portal applications appear to require much more effort and discipline for persistent use amongst less committed consumers or those who are less technology minded, or simply those who can't commit to much effort. It became evident from the PowerPlayer study that a functional simple physical display, but with an intuitive and self-explanatory user interface design, were important for the persistent use of the real-time feedback system. For these consumer groups a simple yet visually appealing physical energy monitor could be a more logical first step to activate consumer interest and engagement in accessing energy information from the smart meter, due to the greater accessibility of the energy data.

Next to the practical user preferences and balanced functionality and data presentation (interface design), the Technical University of Delft also demonstrated that social interaction within the household (family dynamics) will be crucial to the reinforcement of engagement and persistent savings.

A final observation from most experiments and pilots is that the savings achieved from real-time feedback instruments merely originate from simple behavioural changes that require little effort or investment of time or money. These behavioural measures focus particularly on the reduction of unnecessary energy consumption (breaking with 'bad' energy consumption behaviour habits such as leaving the lights on in empty rooms) and reducing base load consumption (such as turning the thermostat down earlier in the evening and checking the monitor before going to bed). These quick-win measures require little effort, yet contribute to savings immediately. In most studies, longer-term measures (investments) such as insulation or double glazing on the other hand were rarely mentioned as a result from direct feedback. Longer-term investments such as high-efficiency boilers, double glazing, roof insulation and solid wall or cavity wall insulation are more likely to follow from indirect feedback, as was suggested in the MijnOxxio-experiment.[22] As a result, direct (real-time) feedback

[22] The study was unable to properly clarify the extent to which this is the result of the MijnOxxio feedback intervention.

and indirect feedback should therefore not be considered as mutually exclusive, Both types can actually complement one another quite well. A real-time display can be the most convenient tool for immediate monitoring and consumption behaviour change at the operational level. Online long view consumption analytics and other indirect feedback tools, such as the bi-monthly energy usage statements, have the potential to become a tactical instrument for interim evaluation and forecasting of annual consumption. Finally the annual bill could become a benchmark for final evaluation of the past consumption year and the determination of a next year's savings goal and / or longer-term investment decisions.

The following section will set out how the main findings in the Netherlands build on the wider international literature already existing on the interventions to change energy behaviour based on smart metering based feedback instruments.

The Dutch smart metering experiments in international context: explanation for benchmarking versus current UK and Irish studies

To help contextualise the headline results from the smart metering consumer behaviour experiments and pilots in the Netherlands, an international literature review of similar trials was conducted alongside this monitoring program. A number of leading international review studies exist in which the potential impact of real-time feedback in particular for awareness raising and energy savings is confirmed. In 2010, the American Council for an Energy-Efficient Economy (ACEEE) conducted a comprehensive meta-analysis of 57 (mostly small-scale and short-term) studies in nine different countries, and found that feedback with smart metering led to an average reduction between 4 % and 12 % in energy consumption, in which case systematically higher savings (9 %) were established in pilots with real-time feedback (Ehrhardt-Martinez et al., 2010). In 2011, another large literature review was released by VaasaETT, by order of the European Smart Metering Industry Group (ESMIG), with a global analysis of more than 100 smart meter pilots, with more than 450,000 households in. The review suggested that smart meters in combination with in-home displays (IHD) were most effective in achieving involvement amongst consumers and most successful in achieving savings, with an average of 8.7 % total (Stromback et al., 2011). Moreover, VaasaETT and ACEEE both demonstrated that the savings were persistent over the measuring periods up to more than a year compared to control groups, and could increase even more through the purchase of more energy-efficient appliances, for example. Other feedback instruments, such as websites and extra informative invoices, showed lower savings (5 to 6 %). In general, the international literature suggests that the more immediate and frequent the feedback, the greater impact on energy consumption (MacLaury et al., 2012).

However, due to differences in research methodology, social cultural based consumption patterns and climatic circumstances, saving results in similar studies in USA, Australia and even some parts of Europe (e.g., Scandinavia, France, etc.) over the past ten years are only limited comparable to the situation in the Netherlands. Much comes from the USA, Canada and Australia, where extreme climate conditions (with regard to security of supply) and different consumption patterns (use of large electric equipment / appliances, such as pool heating, air conditioning, etc.) play an important role. It seems, in general, that countries with the highest peak consumption periods are also observed as the largest outliers in terms of savings achieved.[23] Even research from other Western European countries in the field of smart meters can only be used to a limited extent for the Netherlands. In Scandinavia, for example, nearly all of the energy consumption is based on electricity (especially for heating and saunas), unlike the Netherlands, where a large part of the household energy consumption is related to natural gas.[24] Also research from countries such as Italy, Spain and Portugal is also only comparable to a limited extent, due to the larger number of air conditioning units, which has a major effect on the average reduction in electricity consumption relative to the Netherlands at present.

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[23] Examples hereof are the pilots conducted in Ontario, Canada in 2006 and 2009 (7 % savings for electricity achieved by frequent users), Eco Pioneer Programme in Victoria, Australia in 2009 (15 % electricity and 18 % gas, multiple intervention part). Also, the smart meter was not used in all of the studies.

[24] The electricity consumption in these countries is therefore higher than that in the Netherlands, by an average of 5 times.

Surrounding countries such as Belgium, Germany, the United Kingdom and Ireland are more suitable for benchmarking for the Netherlands, due to more similar climatic conditions, consumption patterns, and a dual fuel energy mix based on electricity and natural gas for room heating, cooking and hot water.[25] However, since only the United Kingdom and Ireland have conducted scientific research at a national level on the effectiveness of savings achieved with the smart meters and additional feedback, benchmarking versus the current UK and Irish studies will be most relevant.

The United Kingdom (UK)

In the UK, the largest consumer study was undertaken in this area in the world to date. The Energy Demand Research Project (EDRP) ran from 2007 to 2010 and considered the effectiveness of savings achieved with the smart meter, in combination with different feedback systems (AECOM, 2011). In this research programme, which comprised multiple trials, including approximately 18,000 households with a smart meter, experiments with smart meters and real-time displays showed consistent and generally persistent savings of around 3% on average for electricity, compared to households with just a smart meter (Smith, 2011).[26] According to the researchers, the achieved savings seemed mostly the result of simpler (behavioural) changes. This was also observed in the Dutch trials as highlighted in the previous sections of this chapter.

Pilots with web-based services did not show any demonstrable savings in the EDRP. However, this technology is developing rapidly and real-time applications for online use on PC, smart phone and tablet (apps) have since been introduced to the market. Online applications are potentially promising, especially due to the comprehensive graphic analysis and presentation options and in combination with the ease of use associated with modern mobile media. It remains to be seen, however, whether online systems will also live up to these expectations in reality. Darby (2010, 2011) states that *in-home displays with an appealing and intuitive interface at an easy accessible location in the house will be a crucial first step for many consumers to attract active consumer interest and engagement in accessing energy information from the smart meter*. Advanced online systems on PC, tablet and smart phone must then not necessarily be seen as an up-to-date substitute for in-home displays, but rather as a complementary option.

As in the monitoring report for the Parliament in the Netherlands, a similar conclusion was also drawn in the EDRP with regard to the mutual relationship between direct and indirect feedback. This was phrased as follows in the final report (AECOM, 2011):

The distinction is important because, although there is a general finding that households take a positive view of feedback, it matters how detailed it is and how closely linked to specific actions, in time and in level of disaggregation. Logically, aggregated feedback (e.g. quarterly or annual consumption) is more relevant to one-off changes that have a persistent impact, such as installing insulation or upgrading a heating system. More fine-grain, real-time feedback is more relevant to routine behaviour and purchases of equipment used intermittently (e.g. washing machines, televisions). By extension, aggregated feedback may be more relevant to the fuel used for heating (most often gas) and real-time feedback to electricity.'

Ireland

A consumer study was conducted in Ireland between 2009 and 2011 to test the impact of the smart meter in combination with different feedback interventions, in the context of the National Smart Metering Programme (NSMP). In the so-called Customer Behaviour Trials (CBT), the responses from a representative group of 7,000 consumers to the introduction of the smart meter in combination with

[25] In England, approximately 85 % of all households use natural gas for heating purposes, on average. In Ireland it is approximately 45 %. Approximately 50 % of households in Germany and Belgium also use natural gas for heating. The Netherlands has the highest percentage of households connected to natural gas, with approximately 98 %.

[26] One trial in the EDRP showed savings to be persistent up to more than a year, other EDRP findings indicated support over time from interventions (e.g. advice or billing information) may be required for savings to be sustained for longer periods.

time-of-use pricing and different feedback intervention types such as periodic home energy reports and a real-time electricity display (developed especially for this study), were observed (CER, 2011). The combined offer of smart meters, home energy reports with bi-monthly invoices and real-time displays in this study led to the highest average electricity savings of 3.2 % overall and 11.3 % at peak consumption intervals.[27] The in-home display led to an extra savings of 2.1 % (4.4 % at peak consumption intervals), compared to households that only received the periodic home energy reports (Foster et al., 2012). The combination of home energy reports and displays also provided the highest savings effect for gas, of 3.6 % compared to households with just a smart meter (CER, 2011).

Concluding remarks

Research in the Netherlands points out that the smart meter, in combination with direct feedback, in particular, can significantly change energy-related behaviour in homes resulting in substantial savings. However, whether households with smart meters and direct feedback interventions will be able to actually achieve average savings of 6.4 % for electricity and 5.1 % for gas as mentioned in the national cost-benefit analysis, remains to be seen. The experiments and pilots indicate that initially achieved savings are only likely to be persistent, if the feedback medium tailors the user's practical preference and if the functionality and data presentation (interface design) match with the consumer's interests and capability for engagement and reinforcement with the feedback system. This means that consumer groups should not only be differentiated in terms of interest for energy savings, but also in different levels of technology-minded engagement. Sophisticated online instruments are potentially powerful to help reduce energy demand, but more so for individual use amongst already committed technology minded subsets of the population, looking to further optimize household energy consumption. The extensive data analytics and graphic presentation options in combination with the ease of use associated with mobile media such as laptop, tablet or smart phone, provide the required added value for habit formation with the web tool. Otherwise, less committed and technology minded consumers or less capable consumers prefer the accessibility of a functional simple yet visually and family appealing in-home display. Although not yet investigated as such, it can be hypothesized that especially for older people, those with low levels of education or low levels of numeracy or computer literacy, for example, an in-home display could be a necessary first step to activate consumer interest and engagement in accessing energy information from the smart meter.

However, different forms of feedback are not mutually exclusive, but can actually complement each other. Direct feedback leads to quick-win measures in particular: simple behavioural changes that seem effortless and don't cost much time or money to implement, yet contribute immediately to savings. Examples include switching the lights off in empty rooms, avoiding stand-by use, etc. Longer-term investments such as insulation (weather strips, double glazing, etc.), are generally not considered as a result of direct feedback. Conversely, long-term measures tend to show up more as a result from indirect feedback and the bi-monthly energy usage statements.

The experiences so far in the Netherlands are fairly consistent with the international research literature. Although not all international research is equally suited for comparison to the Dutch situation, the international consensus is still that the smart meter, in combination with accessible real-time feedback, in particular, can provide the most effective stimulus for awareness raising and the development of motivation amongst consumers to monitor and better manage their energy consumption. Compared to the experiences with feedback through in-home displays in the United Kingdom and Ireland (roughly 3 % on average for electricity and gas), the estimated potentials in the cost-benefit analysis for the Dutch consumer (6.4 % for electricity and 5.1 % for gas), due to direct feedback, are rather high. Even so, various pilots indicate that these potentials are realistic, on the condition that the feedback tool meets the practical user preferences and the functionality and data presentation (interface) fit the consumer's interests and capability. In doing so, habit formation and family dynamics with the tool will become more likely, as well as the persistence of the achieved energy savings.

[27] For comparison to the Dutch experiences, it should also be taken into consideration that these results were also influenced through the application of variable supply rates for electricity and gas.

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A data management platform for personalised real-time energy feedback

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Abstract

This paper presents a data collection and energy feedback platform for smart homes to enhance the value of information given by smart energy meter data by providing user-tailored real-time energy consumption feedback and advice that can be easily accessed and acted upon by the household. Our data management platform consists of an SQL server back-end which collects data, namely, aggregate power consumption as well as consumption of major appliances, temperature, humidity, light, and motion data. These data streams allow us to infer information about the household's appliance usage and domestic activities, which in turn enables meaningful and useful energy feedback. The platform developed has been rolled out in 20 UK households over a period of just over 21 months. As well as the data streams mentioned, qualitative data such as appliance survey, tariff, house construction type and occupancy information are also included. The paper presents a review of publically available smart home datasets and a description of our own smart home set up and monitoring platform. We then provide examples of the types of feedback that can be generated, looking at the suitability of electricity tariffs and appliance specific feedback.

1 Introduction

Research into Home Energy Management Systems (HEMS) is currently developing at a rapid rate, spurred on by the imminent requirement of utility suppliers to be able to supply advanced services for improving customer retention and make their business more attractive. This reinforces the push on research into data collection and analysis and the development of energy disaggregation algorithms [1, 2, 3] as well as the development of activity recognition [4, 5] and other decision support tools to provide much needed energy feedback for long-term user engagement and interaction.

To facilitate the above research efforts, it is important that researchers have access to data which can be used for the purposes of building HEMS, providing effective energy feedback and studying domestic energy consumption behaviour. There are many datasets publically available that contain raw power consumption readings. Some datasets consist of a small number of houses at very high sampling rates of the order of kHz (e.g., BLUED [6], REDD [1]), and others have a large number of houses with low sampling rates of the order of 2 or 10 minutes (e.g., UK HES [7]).

With the UK nationwide rollout of smart meters underway, the UK-based REFIT project aims to provide data similar to what can be expected from UK smart meters, as defined by the Smart Metering Equipment Technical Specification (SMETS) [9] proposal by UK's DECC (Department of Energy and Climate Change). Therefore we chose an 8-10 second sampling rate for electrical readings, similar to what can be provided by households that install a Consumer Access Device in their homes to read the Smart Meter measurements directly [9]. This is a higher rate than the half-hourly rate that can be provided via opt-in to energy suppliers and their trusted third parties should home owners wish to be given additional feedback in terms of general energy usage.

Compared to other experimental datasets, such as REDD, BLUED, which have supplied a number of variables such as reactive/apparent power, energy, frequency, phase angles, voltage and current, our dataset catalogues active power usage as this is the data that will be available to both UK households and utilities. In addition to electricity readings we measure temperature, occupancy and light levels. Our dataset also provides analytical data such as how home automation equipment is used and can incorporate coded qualitative data on domestic activities and technology usage routines. This provides greater interpretative depth compared to similar databases (REDD, BLUED, GREEND [10] etc.) where qualitative data, the occupancy group and building type are not provided so it is harder to draw conclusions on the efficiency of the participants against similar homes.

This paper focuses on the design and development of a data management platform for personalised real-time energy monitoring, developed as part of the UK REFIT project [8], and the potential understanding of household consumption and behaviour that can be inferred from this platform from simple to more advanced analytics. The main contribution of the paper is to demonstrate the ease of energy feedback generation as well as a reliable backend for remotely monitoring real-time data such as active power and environmental parameters. The backend includes a database that enables simple and quick access to variety of quantitative data related to domestic energy research via simple queries. To the best of our knowledge, there is no similar data platform publicly available of the same scale or duration which is supplemented by such in-depth participant information.

The remainder of the paper is organised as follows. Section 2 provides a review of similar publically available datasets and sets out the motivation for this study. Section 3 explains the setup of our data monitoring platform including details of measurements collected during our study. Section 4 details the software and database backend for data management. Section 5 discusses the initial analysis of the data gathered with a view towards improving the quality of personalised feedback that can be generated for households. Section 6 concludes the paper.

2 Review of Publicly Available Domestic Electrical Consumption Datasets

A range of datasets are already available which can be used in a similar way to the REFIT electrical dataset. We review these to help show why our database aims to help supply more in-depth information than existing databases. It can be seen in Table 1 that there are a number of datasets that can be used for advanced analytics such as energy disaggregation. Projects that run for a long period of time (> 1 year) tend to focus on a small number of houses (< 10) (AMPds, IHEPCDS), while short projects, of the order of days or several months, may have a large sample set.

Table 1: Publically Available Dataset Comparison

Dataset	Location of Study	Study Period	# of Houses	# of Appliance Sensors per House	Features	Resolution
ACS-F1 [11]	Switzerland	2, 1 hour sessions (2013)	N/A	100, (10 types)	P, Q, I, f, V, Φ	10 sec
AMPds [12]	Canada	1 year (2012-2013)	1	19	I,V,pf, F, P, Q, S	1 min
BLUED [6]	United States	8 days (2011)	1	Aggregated	I, V, switch events	12 kHz
GREEND [10]	Austria & Italy	1 year (2013 - 2014)	9	9	P	1 Hz
HES [7]	United Kingdom	1 month (255 houses) 1 year (26 houses) (2010 – 2011)	251	13-51	P	2 min
iAWE [13]	India	73 days (2013)	1	33, (10 appliance level)	V, I, f, P, S, E, Φ	1 Hz
IHEPCDS [14]	France	4 years (2006 – 2010)	1	3	I, V, P, Q	1 min
OCTES	Scotland,	4 – 13	33	Aggregated	P, Φ,	7 secs

[15]	Iceland & Finland	months (2012 - 2013)			Energy price	
REDD [1]	United States	3 – 19 days (2011)	6	9 - 24	Aggregate: V, P; Sub-metered: P	15 kHz (aggr.) 3 secs (sub)
REFIT [8]	United Kingdom	2 years (2013 – 2015)	20	11+	P, Energy price	8 seconds
Smart* [16]	United States	3 months (2012 – 2013)	1 sub-metered, + 2 (Aggregated + Sub-metered)	25 circuit, 29 appliance	P, S (circuit), P (sub)	1 Hz
Tracebase [17]	Germany	N/A (2012)	15	158 (43 types)	P	1 – 10 sec
UK-DALE [18]	United Kingdom	499 days (2012 – 2014)	4	5 (house 3) 53 (house 1)	Aggregated P, Sub P, switch status	16 Khz (aggr.) 6 secs (sub)

Active Power (P), Reactive Power (Q), Apparent Power (S), Energy (E), Frequency (f), Phase Angle (Φ), Voltage (V) and Current (I).

The largest dataset in terms of length and study size is HES [7]. However, the monitoring interval is small and sampling rate of 2 minutes is low. This makes it less suitable for energy disaggregation research as it becomes harder to distinguish individual appliances and events. It does however provide information about the recorded households, including type, size and number of occupants.

The OCTES [15] dataset is similar to our own, recording Active Power, phase and energy cost. It has a slightly shorter study duration, a slightly larger study size and data are recorded at a similar resolution to ours. It publically provides the electrical data for each house; however, it does not provide any information about the houses other than their geographical location based on country. The example of analysis given describes the use of a sauna in one household; however, this information is not provided publically, therefore an assumption would have to be made as to the power consumption.

Tracebase [17] is a dataset that contains appliance signatures, which helps disaggregation research. The signatures, obtained with 1 second sampling rate, could be used for training but cannot be used to investigate usage patterns as no information is given with respect to the make or model of the appliances being monitored. It currently contains 43 different devices. Each device has a number of recordings from different days and different houses. Also available in the dataset are readings of date, power and average power sampled at 8 seconds.

In all the above datasets, there is no information about the environment where consumption is taking place. Our platform provides an appliance survey and household composition which will help researchers to develop a much more in-depth picture and allow for more types of analysis. Our dataset has a similar output to the OCTES and ACS-F1 datasets but is unique due to the addition of temperature, light, and movement data augmented with house surveys detailing size, age, heating type, insulation, construction type and information about the occupants, working status and age. Qualitative data gathered from interviews with the occupants of households provide a unique way for researchers to validate results with regards to observed patterns and to reduce the number of assumptions that need to be made.

In addition to datasets other teams have developed backend system architectures which could be used with smart home data collection projects. System architecture [19], such as NILMDB [20] shows a framework designed to scale with the smart grid infrastructure. It describes the storage architecture developed, optimised for time-series data. Issues with the big data aspect of smart metering can include the variance in frequency of readings, although with the UK government standard [9] this is going to be eliminated when looking exclusively at smart meter readings. However proprietary sensors may operate at different sampling rates.

3 Data Collection

The REFIT project aims to provide retrofitting advice to households on the basis of smart home data. The data has been collected and analysed by an inter-disciplinary team of researchers from disciplines including Electronic and Electrical Engineering, Buildings and Civil Engineering, Design, and Sociology. A combination of different methods has generated a wealth of data for each of the 20 households in the study. The data has been collected over a two year period, which has provided electrical, gas and heating data which can be viewed over multiple seasons. During recruitment, households were chosen so the sample varied in terms of technical competence, house age and construction, and occupancy.

These 20 households were selected from a set of 46 applicants to ensure a range of household types including single occupancy, dual-income families with children and retired couples. Respondents ranged in age from ten to seventy four, and were drawn from professions that included students, carers, IT consultants and those not currently in paid work. As all the respondents have signed up to participate in a smart home trial and were therefore interested in experimenting with and learning about smart home technologies in their own homes, they may be considered more representative of early adopters than users engaged in studies that elicit a much broader range of public opinions and perspectives.

3.1 Hardware

Each house was fitted out with an off-the-shelf gateway. The reason for using an off-the-shelf gateway was to minimise time on hardware development and increase time to gather energy data. Our gateway needed to be reliable, compact, and provide a backbone for daisy-chaining additional sensor types which would have required in depth testing and a concrete plan with regards to sensor availability (which has changed since the projects inception). The gateway also needed to be robust to the addition and removal of sensors as and when needed, and compatible with the communications technology widely used in the HEMS market, such as Z-wave and RFX devices operating at 433MHz. The gateway is connected wirelessly to a range of environmental sensors, and via a cable to a separate power monitoring hub. Environmental sensors include temperature, light and occupancy (3-in-1) sensors, and smart plugs, which in addition to returning the active power load of an appliance, can also be remotely switched on/off. The hub is wirelessly communicating to off-the-shelf power sensors: an aggregate current clamp as well as 9 individual appliance monitors (IAMs) for sub-metering, and also provides a real-time display of electricity consumption, in Watts (W) and GBP (£), of the aggregate and 9 appliances being monitored, as well as a comparison of consumption over the past week and month, and over the morning and evening of the previous day (see Figure 1).

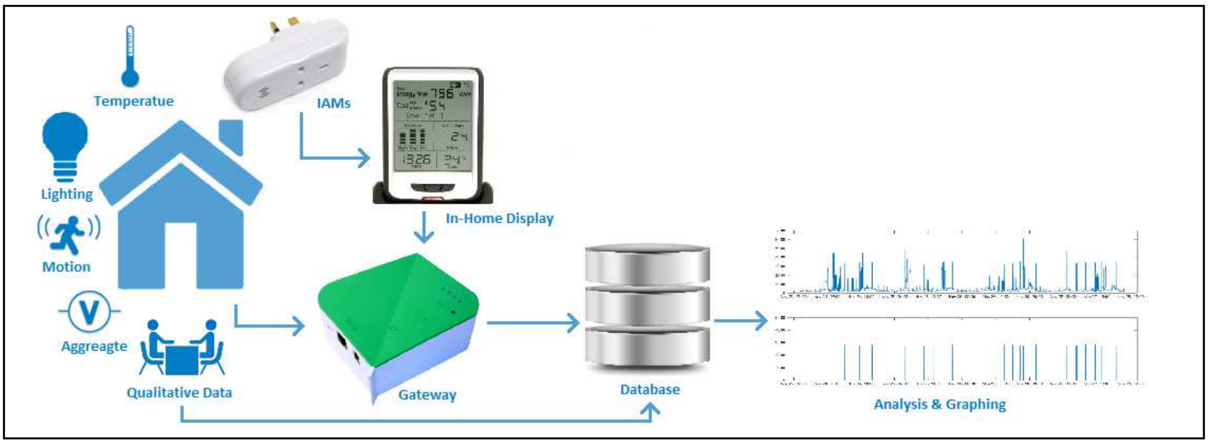

Figure 1: Data collection system

The IAMs monitored high consumption appliances such as white goods, and other commonly used appliances such as televisions. Over the period of study the appliances have in some cases been swapped to reflect an appliance replacement or to gather information about a less known appliance a household owns to augment the appliance signature database and improve the accuracy of energy disaggregation algorithms. Households were also provided with smart plugs which operate similarly to IAMs, although they also have the option to be remotely controlled or set on a timer/schedule via the web-based dashboard.

The home gateway comes with its own web-based dashboard (Figure 2) that allows the REFIT team and the households to organise how sensors are zoned, to name appliances being monitored, and to add additional sensors and automation devices such as remote control plugs, lighting and security sensors.

Figure 2: Online off-the-shelf dashboard

This online interface is the initial point of contact for the REFIT database and allows for real-time remote data collection by the server located at University of Strathclyde. This allows for real-time data management and efficient data collection querying only the sensors whose readings have changed. Each house has around 16 – 20 sensors installed, with readings from most sensors taken every 6-8 seconds.

Some specialised sensors are also available in some houses such as the inclusion of solar panel output monitoring sensors.

3.2 Measurements Catalogued

The quantitative data types stored in our database are shown in Table 2. The resolution of data may vary if a sensor or base station becomes temporarily unavailable.

Table 2: Recorded data

Measurement Type	Sensor Data Capture Method	Resolution	Format (Precision)	Units
Aggregate Load	Current Clamp	8 seconds	Real (-5.5%, +1.4%)	W
IAM	Plug	8 seconds	Real	W
Smart Plugs	Plug	8 seconds	Real	W, On/Off Status
Radiator Temperature	iButton Sensor	30 minutes	Real	°C
Solar	Clamp	8 seconds	Real	W
Temperature	3-1 Sensor	8 seconds	Real (±0.2)	°C
Light	3-1 Sensor	8 seconds	Real	Lux
Movement	3-1 Sensor	8 seconds	UNIX Timestamp + Binary Trigger	Binary

Qualitative data were also collected on the households' ownership and use of technologies as part of their domestic activities. Semi-structured interviews with each household were carried out before the installation of the data monitoring system, focusing on two themes: (i) domestic activities, routines and irregularities; (ii) use of technologies, appliances, rooms as part of domestic activities. Interviews lasted 1.5 - 2 hours, and included a section of video-recorded home tours during which householders indicated, and in some cases, demonstrated or recreated how the residents used technologies as part of their domestic activities. Interview data were recorded, transcribed, and then coded in terms of both activities and technologies. Video data were similarly reviewed and coded using the same template, adding salient information that had not come out in the interviews. The coded qualitative data provides a rich set of contextual information to support the analysis and interpretation of the real-time energy and environmental data (Table 2).

In addition, home surveys were carried out as part of the preparation process for installing the data monitoring system. The home surveys mapped out room sizes and configurations, and the distribution of appliances, technologies and devices. The home surveys provide a snapshot of the physical and hardware characteristics of the home, and provided complementary information to the qualitative data.

4 Database

The database is designed to be as flexible as possible. Households were not all added at the same time, and therefore the database could not be predefined. Data collection also has to be automated along with checking sensors affiliations. Due to the nature of the incoming sensor stream provided by the gateway, MySQL is chosen as it is a powerful open source solution which suited the structured data that was being recorded. MySQL has many benefits as well, when working with a multidisciplinary project, such as easy to use language, good documentation, portability to other systems, ease of integration with other solutions and user friendly tools in which to query the server.

Data are collected via Python scripts which monitor an account connected to each house’s gateway. This setup allows each household to use their own individual gateway as they see fit and a separate project team user account to continue to harvest data without causing any interference. Each Python script is dedicated to its own task, checking gateways are available, checking the sensor availability of each house and a taskmaster that spawns collection processes for each active house. Python was chosen as it has excellent compatibility with MySQL and JSON (JavaScript Object Notation the format which API requests are returned) and therefore is ideally used to bridge between household and database.

The communication between gateway and server is kept to a minimum. To reduce the amount of duplicate records only sensors that have changed in value every 8 seconds are returned and stored. All data are stored with an associated MySQL date-time format based on when the data was harvested, not on the date-time recorded by the gateway as this is not always reliable and is dependent on what time zone the gateway is set to. The date-time format was chosen to make it simple for queries to be completed by those not used to working with UNIX, and MySQL can convert between the two easily when results are being downloaded from the server.

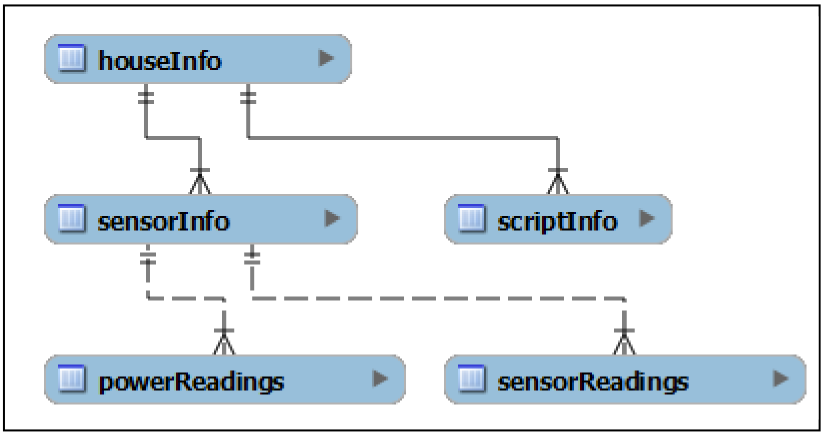

Figure 3: Database layout

The layout of the database is shown in Figure 3. The server is organised into 5 distinct tables: house information, sensor information, power sensor readings, other sensor readings and script timings. This separation of power and environmental readings is done due the much larger number of power readings expected compared to the other sensors, with each house having a 10 (power):3 (environment) ratio in most cases. This arrangement allows a query to be generated, which returns an entire household's power usage in one results table with each column being Aggregate/IAM grouped to a single concurrent timestamp.

4.1 Challenges

Smart home sensors and technology are still in their infancy. There is no defined structure that sensor platforms are required to conform to and in many cases sensors may be designed only to interface with their predefined base station. This provides a challenge since to provide scalability, it should be possible to add different sensors ‘on the fly’ and interface them to the gateway used.

In some cases there have been certain problems with sensor IDs. If the base station is reset or suffered a crash when it recreates its star network, it may assign sensors different IDs to what they previously had. Thus data accountability at the server harvester script must be designed to account sensors by their unique IDs.

During our study, a number of hardware, software and human interaction challenges were encountered. During monitoring, some IAMs ceased to function correctly. This was detected by a long period of time without a value change. These IAMs were quickly replaced.

The gateway used in the study has a reasonably well thought out API for querying each household to gather sensor readings; however, a standard response format for every type of query would greatly improve usability. One such example is a request for the sensors that have generated a new reading since the last query; this option, however, does not return all of the information that will have remained static between calls, such as static IDs, which can be used for identifying the sensor without the need to keep an up-to-date record of its variable assigned IDs. This means that certain useful IDs are not returned, for example, the sensor UUID (Universally Unique Identifier) which would be extremely useful. This however is only available via a different API query and returns multiple variables without a format such as JSON or XML (Extensible Mark-up Language) and would require regular expressions to validate every time, which adds complexity and creates the need for much more stringent error checking. The other option to query every sensor would have generated a lot more traffic and records which would not have provided meaningful data as in most cases it would be reporting the same value as it had during the last query.

Finally, human interaction is one of the most difficult issues to account for. In some cases, appliances were changed or moved without informing the research team in contact with the households. This is normal for real-world research with households in their domestic environments, but presents a challenge for database management. Similarly, the 3-1 sensors could be positioned poorly or moved without the research team’s knowledge for periods of time. In general, however, most of this activity is logged correctly and can be correlated against other device usage.

4.2 Remote Data Checking

Data checking is essential and where possible has been automated. Scripts automatically reconnect to household gateways when they become unavailable and check the following variables to ensure that data is still being collected: time since the script last managed an update, time between sensor readings and change in sensor readings. The gateways also allow for multiple accounts to have access; this enables remote resets as well as performing updates by the research team if the household did not notice or check via their gateway’s internet portal. If a sensor has been disconnected or has stopped functioning correctly, this was recorded and a member of the project team physically replaced the sensor.

5 Data Analysis

This section presents some examples of analytics that are enabled by our platform, and hence the potential for more salient and meaningful personalised feedback to households.

5.1 Aggregate Power Load Analysis

The database facilitates simple analytics, such as direct household comparison at the aggregate or plug level, and can give a more detailed breakdown than what is given via utility power bills. Seasonal usage can also be broken down much more precisely, and when correlated with temperature differences, can be used to explain increased usage especially with respect to gas. This kind of analysis is quick and easy to do and can be provided to households without the need for any expertise.

Comparison of different tariffs can also be done quickly, since data are collected at 8 second intervals. The suitability of specialised energy tariffs such as Economy7 can be analysed. Economy7 is a tariff available in the UK which consists of a day cost and an off-peak cost (between 10pm – 8am depending on location and supplier). It is an ideal tariff for households that use electricity for storage or water heating and for those who use electricity significantly more during off-peak hours.

Table 3: Suitability of Economy7 electrical tariff

House ID	Supplier	Tariff	Minimum Night Usage to Breakeven (%)	Actual Off-peak Usage (% of Use)
1	Scottish Power	Economy7	28	28 (00:30 – 07:30)
2	Good Energy	Standard	-	12
3	Npower	Standard	-	12
4	E.ON	Energy Plan	-	19
6	OVO	New Energy	-	17
7	Scottish Power	Economy7	28	13 (00:30 – 07:30)
8	EDF	Blue Price Promise (E7)	22	46
12	E.ON	Energy Plan	-	14
13	M&S Energy	Standard	-	16
15		Economy7	-	20
16	Utility Warehouse	Gold	-	22
17	British Gas	Standard	-	13
18	Npower	Price Protector	-	17
19	Good Energy	Economy7	30	19
20	Npower	Standard	-	17
21	M&S Energy	Economy7	29	17

The percentage of use is the % of power consumption during the indicated time periods. Actual off-peak period set by the supplier is 12am – 7am unless specified, e.g., House 1. Consumption figures refer to the period September – December 2014.

Table 3 shows tariff and off-peak energy consumption values for a selection of houses. It can be seen that a number of houses are on non-standard tariff; in all cases tariffs that are not 'Economy7' should be considered single rate. The minimum night usage column shows the amount of usage required to break even against the same supplier's standard tariff when using Economy7. The last column shows the actual off-peak usage of the household, which is to be compared with the previous column to determine whether the household is making the most of their tariff.

Using the latest figures from the utility websites [21, 22, 23, 24], it can be seen that to benefit from the Economy7 tariff a household would have to use a minimum of 22-30% during the off-peak rate. Looking back at Table 3 it can be observed that only 2 houses benefit from being on an Economy7 tariff: House 8 where over 40% power usage is off-peak and House 1 which is on the limit of minimum usage for their specific tariff. The other houses on Economy7 fall short of this minimum target (Houses 7, 19 and 21) and will in many cases be paying more than if they were on a standard tariff. Those on Economy7 should look at adjusting large white appliance schedules such as dishwashers, washing machines and tumble dryers to make better use or consider switching tariff to reduce costs.

Figure 4 shows the usage time of washing machines in the two households. It can be seen that House 8, which is very energy conscious, schedules all of their laundry to fall within the 12am – 7am period. This is reflected in their night usage shown in Table 3. House 1 is just meeting their off-peak usage. Their laundry schedule shows that they do not rigidly stick to the off-peak timings. Washing machine uses between 10am and 12pm can be observed. A schedule change to adjust these washes to begin at 12am would help to improve their off-peak usage and save money.

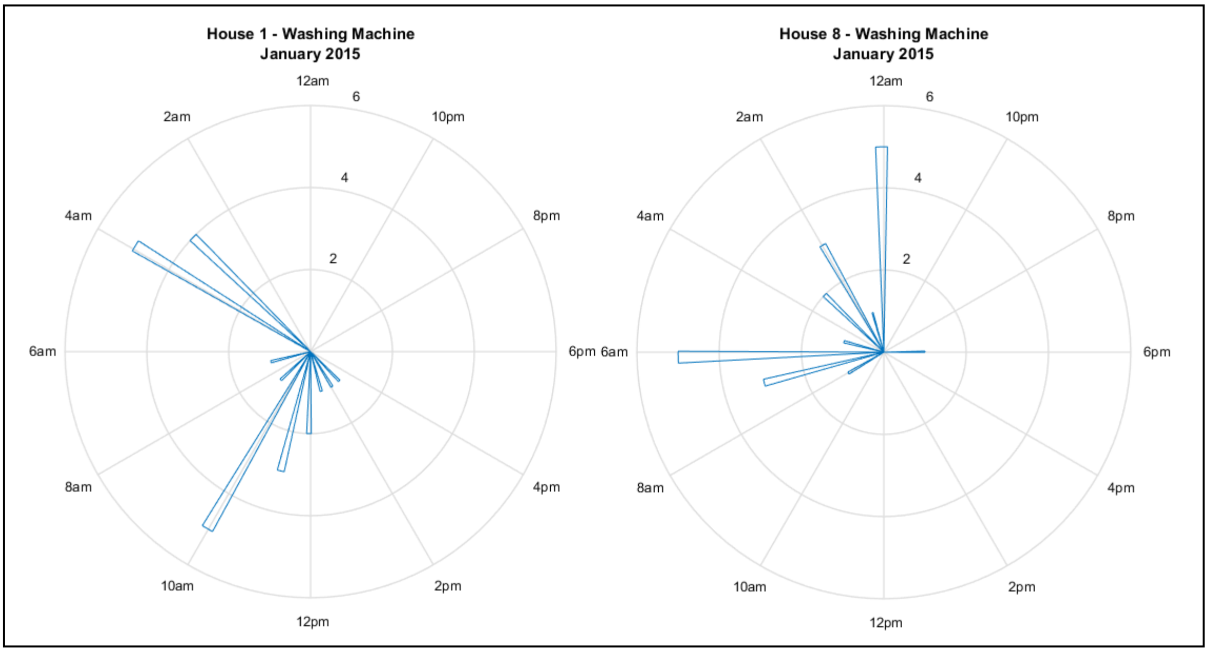

Figure 4: Washing machine usage time. Values refer to the number of washes started during each hour during January 2015.

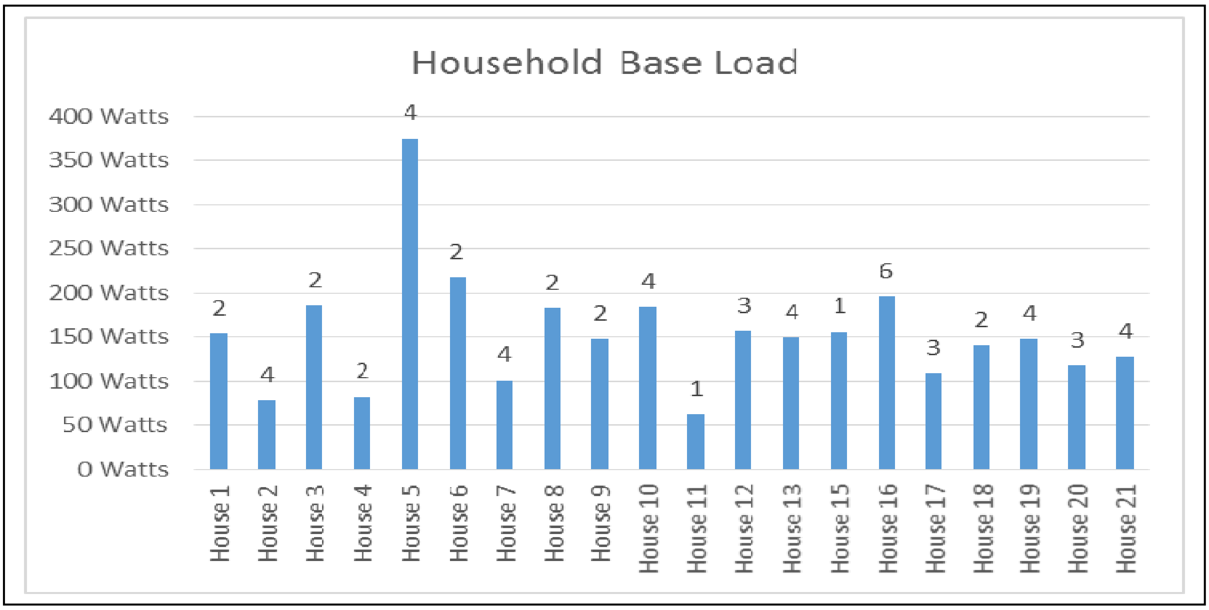

Figure 5: Household base load. The base load is the minimum level of demand on the household's supply system over 24 hours. Data recorded January 2015. Number at the top of bars represents the household occupancy.

Figure 5 shows the base load (the lowest most frequent value) extracted from the aggregate load data; this is a good indication of the number of appliances being left on standby or background appliances such as boiler control units, fridges and freezers. A high base load can be investigated by the household. Benchmarking with other households, households may be motivated to evaluate what they are leaving on or in standby and decide if this is really necessary. The costs can also be significant; considering the cost of an average UK electricity tariff, House 5 could be spending up to £40 per month on background appliances, representing a substantial cost per year and highlighting the need to investigate the probable causes. Our data revealed that the computer in House 5 is left on almost continuously, thus contributing around 150W continuously to the base load.

Figure 6 shows the percentage of total consumption contributed to by the base loads. DECC published early findings from HES [7, 25], which places average baseload at around 220W which is consistent with our findings shown in Figure 5. A yearly consumption on average across the UK of

4,154 kWh, a baseload of 220W continuously over the year would consume 1,927kWh meaning that baseload would account for 46% of total consumption. Figure 6 shows that most of the houses in our study are below this threshold. House 15 has a significant percentage being the baseload, however this can be attributed to computers which are left on constantly throughout the year. House 5 can be seen to have a very high baseload (see Figure 5), but this only accounts for a small percentage of total usage because House 5 is a high consumer.

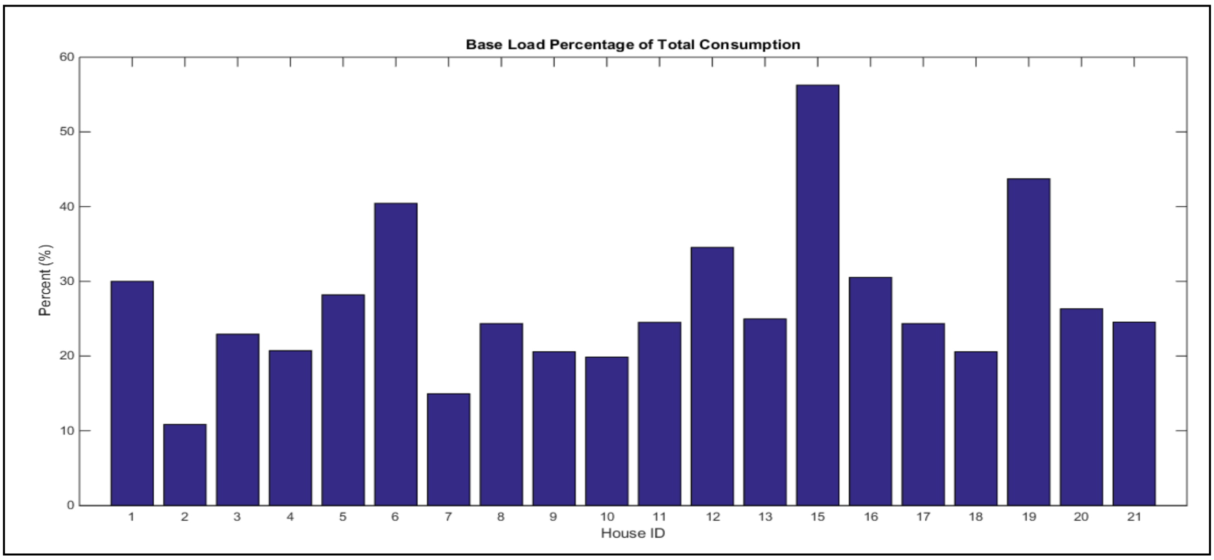

Figure 6: Base load percentage contribution to household total consumption, using data for the month of January 2015.

Due to the nature of the database layout, importing and exporting data is made easy and therefore raw data can be provided to be used by households if they wish to look at certain events themselves. This would be provided as a csv file with a single time series and the labelled sensors, location and units associated with that house.

5.2 Appliance-Specific Usage

Appliance usage analytics is easy to obtain from our database as the high consuming devices are monitored individually. Appliance benchmarking and usage habits can therefore be easily extracted. Additionally, these data streams can be used for validating power disaggregation algorithms that are being developed. Appliance benchmarking is something that along with usage cost can be fed back to the household to visualise information. However, there is a separate issue of privacy and consent when sharing data across households. In many cases appliances may not be performing as well due to age or other factors. An example of how the data can reveal inefficient fridges can be seen in Figure 7. This shows the raw fridge active power time series consumption, which highlights the frequency of operation as well as the power usage. Figure 8 shows a probability density function to display the range at which the fridges operate. Finally, Table 4 shows the expected costs.

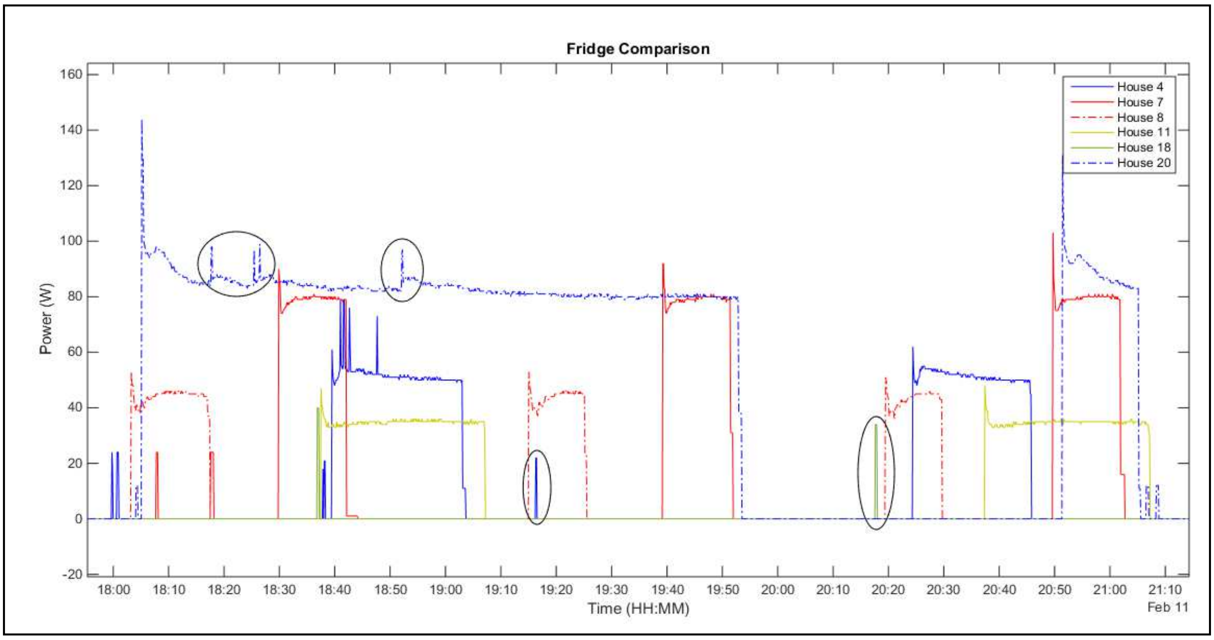

Figure 7: Fridge power comparison plot

Figure 7 shows the different operating characteristics exhibited by some of the fridges. It can be seen that they all have similar signatures. However the frequency and duration vary significantly. The areas circled indicate the fridge door being opened and hence how often the fridge is used, that is, the longer the door is left opened, the higher the consumed load. This plot is very useful to researchers to assess efficiency of fridges, but not necessarily for households to visualise. All fridges have a starting edge spike that is attributed by the fridge motor.

Figure 8 shows the probability density function (pdf) of each fridge from Figure 7, which helps to visualise the power efficiency characteristics of each fridge, i.e., how often each fridge works within a particular power range. For example, House 11 has a high narrow curve in the lower end of the consumption axis, and consumes less than Houses 18 and 20. This is shown in Table 4, which provides details of the annual cost of running fridges in different households. Both Figure 8 and Table 4 clearly show that House 20 owns the most energy-consuming fridge. However, this does not take into account the fridge's volume, which is a major contributor to consumption, nor the type (e.g. whether the fridge has a built-in ice dispenser). Similar confounding factors related to appliance characteristics apply to appliances such as TVs for which screen size and features will contribute to both power usage but also consumer appeal. The approach demonstrated in Figures 7-8 and Table 4 can however help to highlight highly inefficient appliances and provide recommendations to help households upgrade appliances to save energy and money in the medium-to-long term.

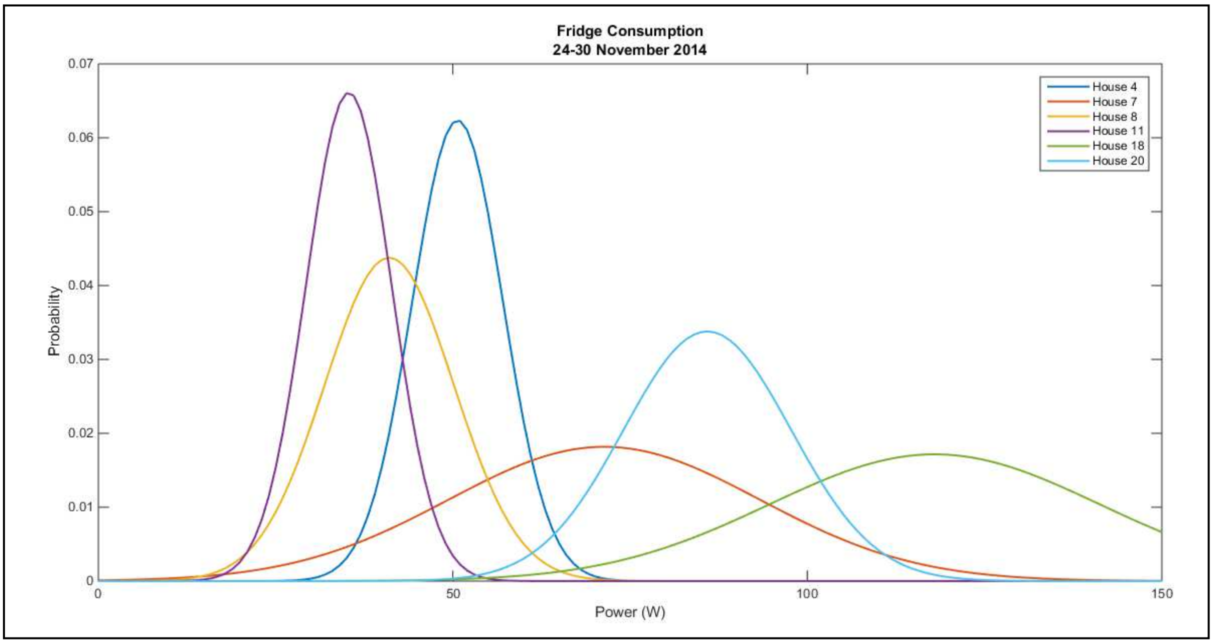

Figure 8: Fridge power bands

To help convey this information to households in a meaningful manner, Table 4 is provided with the associated power consumption along with financial cost.

Table 4: Comparison of fridges in six houses.

House ID	Average Duration (s)	Average Active Power (W)	kWh per Year	Cost per Year (14.05p/kWh)
House 4	1130	51.7	81	£11.38
House 7	535	67.9	114	£16.03
House 8	832	42.1	63.4	£8.91
House 11	1736	34.8	117.9	£16.56
House 18	408	117.8	135.6	£19.05
House 20	1109	89.1	241.8	£33.98

Table notes: Data recorded February 2015. Average duration is the active period during normal cooling. kWh per Year extrapolated from cost of February.

Analysis on individual appliances allows usage patterns to be analysed daily, weekly, monthly, seasonally and so on. These patterns can reveal specific routines, for example, laundry on alternate days or the duration of time spent watching television. Alternatively analysis can show the time when entertainment-related appliances have been left on standby.

Table 5: Monthly energy consumption of television and ancillary components

House ID	Consumption (kWh)	Standby Consumption (kWh)	% of Consumption Attributed to Standby	Hours in Standby	Cost per Year (14.05p/kWh)
6	31	6	22	523	£4
8	31	5	16	602	£4
9	21	5	24	586	£3
17	12	7	58	652	£1
19	10	5	51	643	£1

Table notes: Data collected January 2015. Ancillary components include set-top boxes, games consoles, etc. 14.05p stands for 14.05 pence or GBP0.1405, which is the average electricity tariff in UK in February 2015. [http://www.energysavingtrust.org.uk/]

Table 5 illustrates the effect that standby has on energy consumption. In some cases over half of consumption associated with the IAM is standby. In the case of Houses 17 and 19, there is large portion of usage in the standby power range. From the hours left in standby, it is clear that the television and associated devices, including set-top box, game consoles, DVD players, are never switched off at the socket point. Completely turning off any non-essential devices in these houses could amount to a reasonable saving over the course of a year. The other houses have a larger period of time in use but the consumption of standby devices is still significant and feeding this information back to homeowners may make them re-evaluate habits with regard to fully switching off appliances.

6 Further analytics enabled with our platform

Initial work on further analysing the quantitative and qualitative data collected using advanced algorithms, e.g., Nonintrusive Appliance Load Monitoring (NALM) [2, 3] and activity recognition [4, 5] has shown the potential of our platform. Activity recognition allows electricity usage to be apportioned between activities such as cooking, cleaning, washing, laundering, watching TV, and playing computer games. This is a potentially powerful means of providing feedback as it reflects households' own lived experience. We note that while some other datasets publically available, such as BLUE, GREEN, REDD, can be used for NALM, they cannot be applied to activity recognition due to the lack of qualitative data necessary to associate accurately appliance usage to domestic activities.

Gas data together with available temperature data will facilitate gas disaggregation which differentiates the gas consumption used for space, water heating, and gas hobs used for cooking. Gas and temperature monitoring will also enable the development of statistical building energy models and allow the accuracy of conventional steady-state models to be tested [25].

The dataset also enables other types of analysis. As an example, [26] investigates the reception, adoption and influence of smart technologies and the usage of remote control smart equipment, by analysing available qualitative data in relation to remote/scheduled usage patterns logged in the database. Another example is [27] which looks at the available house data and associated power usage and how this can be used to generate retrofit advice which is then fed back to occupants in a way where they will be in position to make informed decision about retrofitting their house.

7 Conclusion

This paper has laid out the different components of the REFIT monitoring platform and dataset, and some of the possible information that can be gleaned about consumer habits with a view to promote energy saving behaviour via meaningful feedback. We have shown that households and appliances have distinct energy consumption patterns, and thus a personalised approach is needed.

The results demonstrate the progress towards our goal to provide an easy to use in-depth study on a number of houses for use by researchers to perform disaggregation and household analysis from multiple perspectives with the ability to combine data gathered from different fields of study. We hope that by fairly representing the UK Smart Metering Equipment Technical Specification, home energy management systems can be developed using similar in-depth datasets, like ours, that takes into account the additional meta data provided alongside power which can be used to help tailor the platform to the intended market.

Acknowledgements

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Online Web Application with Local Database Storage for Residential Energy Auditing and Education

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Abstract

The residential sector represents a sizeable component of the typical national electrical load profile, especially in the morning and evening peak load periods. This has given rise to growing efforts to improve household energy management and energy efficiency through initiatives such as minimum energy performance standards for electrical appliances, automated load scheduling systems and consumer education. A considerable number of energy management and energy auditing software applications, including online web applications, have been developed in recent years to educate residential consumers in energy management matters. Generally, the system topology of an online web application features a browser-driven user interface that connects to a remote database server that maintains up-to-date information of appliance performance specifications and user system information.

This paper discusses the development of an interactive rich internet application for residential energy auditing that implements a hybrid database configuration consisting of a remote relational database backend in combination with a local SQLite database structure. This hybrid database topology offers a number of distinct advantages, including increased security of user data, the possibility of offline system configuration and auditing functions, reduced network traffic, substantial simplification of the user management system on the remote server and improved scalability.

The optimal design of the local and remote database structures is discussed and the demarcation of functionality between the local application and the remote server is investigated. The data exchange protocol for communication between the local and remote is introduced and discussed from a performance perspective. Requirements for cross-platform support and compatibility among the contributing technologies are examined.

Overview of the South African electricity market

South Africa is experiencing electricity supply capacity constraints, which have highlighted the need for major restructuring of the local electricity supply and demand market. This restructuring is characterized by an expansion of both conventional energy sources and alternative sources such as renewable sources and the acceptance that independent power producers may become part of the future power generation scenario. Acknowledgement of the need to restructure is evidenced in recent government actions such as a request for information to lobby participation in the development of strategies for demand response and/or distributed generation initiatives, issued under direction of South Africa's Department of Energy (DoE) [1]. The general rhetoric echoed by the South African public and stakeholders are calls for reform, deregulation and open access [2].

On the demand side, demand reduction is conceptualised as a resource that can be treated as a supply resource and this "*resource*" perspective is expedient in restructured markets [3]. Aligned with this view is the argument to promote increased incentivised Energy Efficiency (EE) on the demand side, which has been described as "… *a secure domestic fuel that produces year after year after year – cleaner/less polluting than fossil fuels, with a smaller footprint than renewables*" [4]. It has likewise been argued that the rational use of energy must be viewed as a "*concealed energy source*" and not just a contingency plan [5].

In accordance with Demand Management (DM) programmes approved by the National Energy Regulator of South Africa (NERSA), high price periods during times of peak demand are demarcated for high consumption sectors such as manufacturing and mining, when customers are expected to reduce their load through Energy Management (EM) measures such as load shifting and EE interventions. On the residential front, no dynamic pricing scheme such as a Time of Use (TOU) tariff structure has yet been implemented, although a sliding scale tariff or Inclining Block Tariff (IBT) exists whereby a residential consumer will pay more upon exceeding a certain monthly kilowatt-hour (kWh) threshold. According to this structure, higher consumption customers are charged more based on their electricity usage as an incentive to regulate monthly consumption. The South African supply utility, Eskom, published the following response during an IBT public hearing: "*Residential tariffs should be segmented based on justifiable consumption categories such as low, medium, and high usage or based on the customer's installed capacity.*" [6]

The IBT system is hampered in practice due to technical constraints inherent to the billing system, especially where pre-payment metering systems are in use. An IBT structure requires monitoring of customer consumption on a monthly basis in order to allocate the consumption to the relevant block, allowing for customers to be charged the applicable rates according to their consumption levels [7]. The current pre-payment IBT implementation involves recording the monthly amount of electricity purchased by a consumer, not the amount used, relegating it to a rationing system. Calculation of pre-paid tokens purchased is for a calendar month where tokens add up the number of kWh units. When the total purchased kWh reaches the next tariff block, fewer units will be received for the same amount of money. For example, the purchase of prepaid electricity on the last day of the month may be at a high tariff while on the first day of the next month may be at a low tariff regardless of consumption [8]. The intended message of "*The more energy you use, the more you are going to pay*", is thus not entirely accurate.

TOU tariff structures, such as the "*Homeflex Tariff*" [9], are under consideration for the residential sector, but requires wide-scale installation of smart metering systems. The rollout of smart metering systems to residential consumers is, however, well advanced in most of the major metropolitan areas. In this changing energy landscape, the education and empowerment of residential end-users in managing demand, thereby reducing costs and promoting efficient use of the available resources, represents a valuable investment.

Domestic appliance ownership

South Africa has experienced a marked increase in ownership of domestic electrical appliances, due to increased electrification rates and the purchasing power of a growing middle class [[10], [11]]. Appliance labelling and the need for accurate performance characterisation of appliances have become a focus area with mandatory performance standards being issued [12]. In order to address inconsistent product identification and energy performance criteria for appliances, the South African National Standard (SANS) for Energy Efficiency for Electrical and Electronic Apparatus has been published as benchmark. This standard is aligned with the recognised International Electro-technical Commission (IEC) standard. A mandatory appliance labelling programme is being implemented in conjunction with Minimum Energy Performance Standards (MEPS) for a range of household appliances [12].

Implications of MEPS and S&L for energy efficiency

Standards and Labelling (S&L) programmes are drivers of energy efficiency and conserve electrical power [10]: *"… labelling and minimum energy efficiency (performance) standards (MEPS) for appliances and equipment, … have proven to be one of the most essential policy options in developed countries' portfolios for energy efficiency and climate change mitigation programmes."* This observation has been confirmed by the Collaborative Labelling and Appliance Standards Program (CLASP) on how minimum standards and appliance labelling respectively push and pull the market to higher efficiency [11].

A large portion of the current appliance market in South Africa involves inefficient or second hand appliances/equipment selling at low prices. The price of high-end energy efficient products cannot compete with the affordability of second hand or less efficient alternatives. The great disparity in income amongst South Africans also leads to extended appliance lifecycles in the sense that inefficient appliances that are replaced resume a new life of continued use. Furthermore, in countries where S&L are implemented and regulated, a sizeable market segment is sustained by inefficient appliances/equipment that do not meet programme standards [10].

Other than an energy label, an appropriate medium such as an appliance user manual should not only provide power consumption information to the user, but also additional guidance on how to increase efficiency to reduce energy consumption. Otherwise, the user may be left with the notion that he or she should simply use a particular appliance less often, which is problematic with regard to appliances that users must use on a regular basis, e.g. refrigerators and washing machines. Used correctly, an appliance such as a washing machine can exhibit improved energy efficiency:

- At full load using a verified "eco" program selection.
- A cold water wash cycle used in combination with an effective detergent.
- A warm water inlet connected to a solar water heater geyser for a standard 60 °C cotton cycle wash.

Demand Response initiatives

Demand Response (DR) programmes elicit participation from end-users in order to conserve electricity during periods of peak usage. Due to electricity supply capacity constraints, South Africa has been running a voluntary DR programme designated *Power Alert* aimed at residential consumers for the past number of years. This programme makes use of television and radio broadcasting technologies to call on consumers to reduce load at peak periods when the power system experiences supply constraints. Recent studies have consistently indicated that residential consumers can contribute a significant reduction to the electrical load, especially during morning and evening peaks, if end-users are provided with detailed energy-consumption information and appropriate analytical tools [13]. A holistic approach, which incorporates considerations such as lifestyle preferences, a user's level of understanding of consumption, day of the week, time of day, weather conditions, the size, location and orientation of the residence (i.e. north-facing in South Africa or not) and occupancy supports a constructive response.

An EM policy whereby the residential end-user adjusts the time of day of appliance usage in response to a TOU tariff can contribute a significant demand reduction in peak periods, thereby improving the demand response impact as well as increasing disposable and discretionary income. Modern Advanced Metering Infrastructure (AMI) and DR technologies deliver real-time energy usage information to end-users, allowing them to recognise consumption patterns and identify the relationships between appliance use, lifestyle choices and the associated costs. Educating consumers about their usage patterns and EM options can also significantly improve energy conservation and efficiency [13], especially in the absence of AMI technologies. Educational tools that disaggregate the overall energy consumption profile, together with analytical tools for load profile analysis, can teach users how to implement effective EM interventions, especially for TOU electricity tariff scenarios.

Demand response incentives may encourage a residential end-user to implement an Energy Conservation Measure (ECM) such as changing the way an appliance is used to reduce consumption or replacing an inefficient appliance with a more efficient one. Avoided energy usage can be determined using a simplistic application of the following Measurement and Verification (M&V) principles [14]:

- Define the measurement boundary:
  - Model the residence as whole facility, or alternatively
  - Isolate an area in the house, e.g. the kitchen.
- Within the measurement boundary, conduct an appliance audit to determine the installed capacity.
- Determine baseline consumption for one or more appliances.
- Upon implementing an ECM, compare the baseline to the new consumption profile with the view to determine avoided energy use.

Baseline

Without the benefit of measured energy consumption data, the baseline is conjectural and not directly observable, although a consumer may have fairly accurate information on the baseline consumption levels [3]. Conceptually, the baseline represents the estimated level of "*normal*" or "*business as usual*" consumption, estimated from data that represent the past behaviour using statistical estimation methods. From an M&V perspective, measured consumption after an ECM has been implemented enables the calculation of savings [14]. A report on electricity markets and policy [15] confirms the general fact that with measures such as the adoption of stricter building energy codes and minimum efficiency standards for appliances, the baseline against which savings are measured is lowered, thereby influencing both the scope of the remaining savings potential as well as the available technology options.

The IBT incentive in South Africa may be viewed as a form of DM programme. However, in the absence of TOU smart metering support, the IBT billing system has intrinsic shortcomings. An appropriate methodology requires an estimate of the customer baseline consumption profile from which the financial benefit of reduced consumption can be determined. As noted previously, this is not the case in South Africa where a large portion of residential customers use pre-paid electricity meters.

Energy audit of domestic appliances

Innovative complementary technologies have evolved that make it possible for residential consumers to conduct very comprehensive energy audits. Nonintrusive Load Monitoring (NILM) and load signature analysis techniques have advanced considerably as a means to disaggregate a complex load profile into contributions by individual appliances [16]. Event-logging or recorded changes in active and reactive power that correspond to a load either turning on or off is one of the fundamental principles that have been employed [17].

Currently, specialised Integrated Circuits (ICs), that utilise Hall effect current sensing technology, for example [18], are combined with standard communication protocols to facilitate smart meters, home energy management systems and smart plugs. By creating an interface between a measuring and sensing system and individual loads, real-time energy usage can be monitored and controlled.

Conceptualization of an energy usage software application

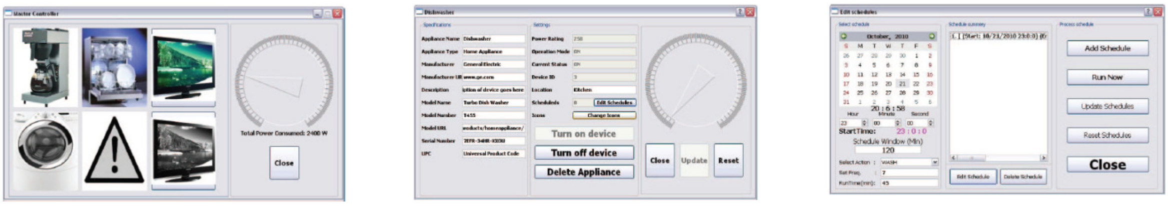
Energy management programmes and web tools

The concept of an EM dashboard or management tool is well established and a number of benchmarking and energy-saving tools for various industries have been developed in recent years. One example for the residential sector is the online Do-It-Yourself (DIY) home energy audit and household carbon footprinting tool, *Home Energy Saver* (HES), created for the U.S. Department of Energy by the Lawrence Berkeley National Laboratory (LBNL) [19]. This tool has achieved success and has been awarded for its effectiveness [20]. It caters for energy efficiency options based on criteria such as additional cost, energy savings, simple payback period and rate of return on investment.

Some commercial web-based EM tools have proved less successful, notably Google's *PowerMeter* and Microsoft's *Hohm*. Attempts to explain their failure include the omission of a platform to connect consumers and utilities and it has been suggested that market entrants in the form of "*lightweight*" reporting applications who hoped to solve platform requirements afterwards, have been unsuccessful. Many smart-grid programmes have also remained in the pilot stage and companies with consumer smart-grid products face difficulties in winning over customers, particularly in utility-led programmes [21]. For the U.S. context, the following has been noted in assessing the usefulness of enabling technologies that generate metrics such as consumption reports: "*There are gaps in our knowledge about both the size and persistence of the load impacts; the heterogeneity in load impacts across customer segments; and the extent to which the customer response in those pilots can be extrapolated to other customers, utilities, and regions of the country.*" [22] These observations are considered to also hold true for the South African context.

The personalised home energy management system for residential demand response supported by the California Institute of Energy and Environment (CIEE) of the University of California, Berkeley [23], features similar research in some respects to the application described in this paper. Figure 1 shows a few of the features of this home energy management system:

- A list of household appliances is displayed as clickable icons.
- For a selected appliance the properties screen is displayed to provide appliance information, control and real-time power consumption.
- A scheduling screen supports activation/scheduling of the appliance [23].



Main dialog box Appliance properties Appliance scheduling

Figure 1 Home energy management system for residential demand response [23]

The EnergyUsageAIR application

The software application described in this paper has been developed as a residential energy auditing tool to visualize energy consumption in the context of residential occupancy spaces, end-use technologies and usage patterns. The functionality offered by the application incorporates the following M&V concepts:

- Definition of a measurement boundary.
- Enabling the user to conduct an appliance audit within the boundary, by utilising and consulting appliance label information to verify installed capacity.
- Creating and associating usage profiles with appliances. These usage profiles are defined in terms of switch-on times and operating durations.
- Determining baseline consumption for any arbitrary selection of appliances and the associated usage profiles.
- Upon implementing an ECM, evaluation of the new consumption scenario against the baseline to determine avoided energy use.

It is important to note that determination of the baseline and post-intervention consumption profiles involves estimation and simulation as neither relies on direct online measurements.

The layout and functionality of the application is based on the concept of a customized virtual residence that can be constructed from a generic set of occupancy areas and associated household appliances. The virtual house has dynamic properties in that the user can make changes and view the outcomes by means of inventories and usage profiles as illustrated in Figure 2.

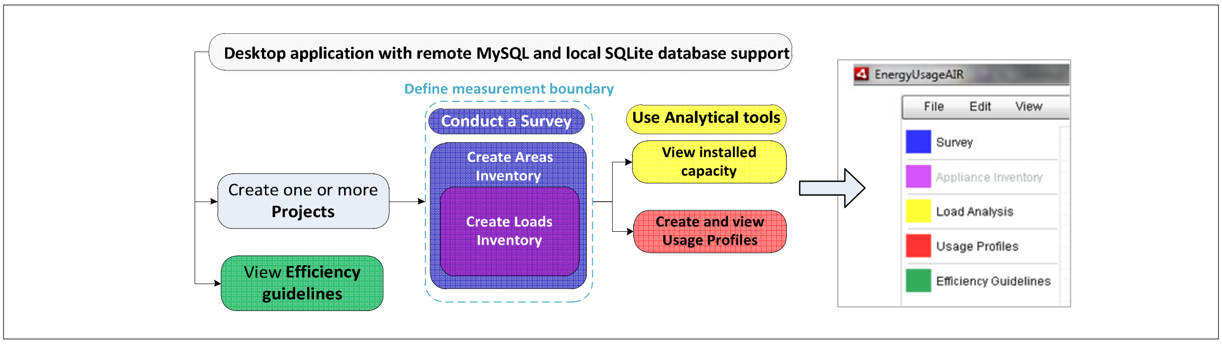


Figure 2 Overview of the application design, functionality and navigational layout

The application was initially designed as a web-based Rich Internet Application (RIA) with only remote database support [[24], [19]]. It has subsequently been redeveloped as a Flex AIR desktop application with both a remote MySQL database and local SQLite database.

Figure 2 shows that a user's virtual house is linked to a specific project, which is created and then populated by combining a set of occupancy areas and the appliances associated with those areas. This task involves the definition of a measurement boundary and conducting an appliance audit. The end result should be a realistic representation of the user's home and household appliances. The coloured block design supports "*recognition rather than recall*" [25] by associating functionality with a specific coloured block to make navigation more intuitive.

Based on the following choices, appliance usage scenarios in the form of profiles may be created as part of a baseline or after an ECM has been implemented:

- Type of appliance(s).
- Number of appliance(s).
- Time and duration of use.

The *Efficiency Guidelines* section contains appliance-specific guidelines to improve the energy efficiency of domestic appliances. The information for this section is provided via queries to the remote server, based on an appliance selection by the user. Selections are hierarchical, including the choice of an end-use category and finally the choice of appliance.

Technology choices and data exchange framework

The rationale for using a hybrid database topology in the form of a remote MySQL and a local SQLite is to achieve the following:

- Minimise remote data storage.
- Improve security by reducing the risk of Structured Query Language (SQL) injections, which in turn compromise data integrity.
- Separate generic and personal information whereby the user can access generic information from the remote server and store a personal home topology and appliance inventory in the local database.
- Facilitate regular and seamless updates of appliance and guideline information on the remote server without a request for the user to install a newer version of the application.

The application utilises the following technology:

- Flex AIR and ActionScript technology.
- Hypertext Preprocessor (PHP) as a server-side scripting language.
- MySQL remote database on an Ubuntu/Linux server.
- SQLite local database.

Figure 3 illustrates the data exchange framework between the remote and local databases.

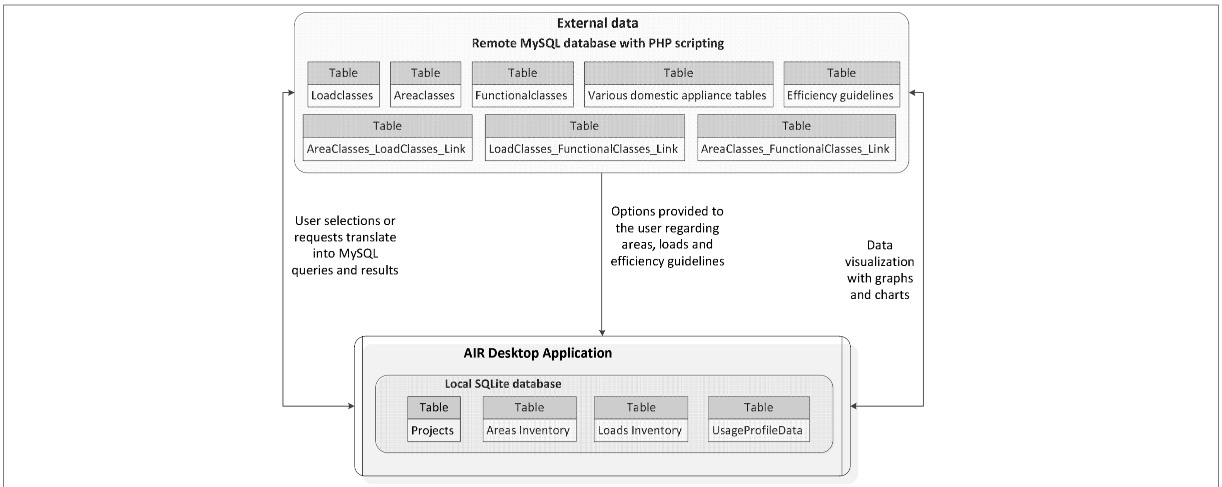


Figure 3: Data flow schematic for hybrid database topology

Remote MySQL database

As shown in Figure 3, the remote MySQL database implements a relational database model, in order to establish relationships between tables that are one to one, one to many and many to many. The remote database structure and content are respectively aligned with its two-fold purpose of providing a relational model and appliance information.

Relational model information

1. *End-use categorisation*

Functional classes were identified to depict end-use categories, similar to those identified by Willis [26] and employed by the Bottom-Up Energy Analysis System (BUENAS) [27]. The BUENAS' end-use coverage in the residential sector comprises a wide range of energy-consuming products, including most end-uses generally covered by Energy Efficiency Standards and Labelling (EES&L) programmes around the world. As indicated in Figure 4, the residential end-use categories currently covered are: Air Conditioning, Cooking and Dishwashing, Fans, Lighting, Refrigeration, Space Heating, Standby, Televisions, Water Heating and Laundry. In respect of BUENAS, the model as originally created sacrificed some detail in order to cover as many end uses as possible, whereby products were grouped into categories rather than being modelled as individual technologies (e.g. refrigerators and freezers are grouped into a single "*refrigeration*" category) [27].

BUENAS End-use / Country

Sector	End Use Category	Appliance
Residential	Air Conditioning	Air Conditioner
		Central AC
	Cooking + Dishwashing	Cooking Products
	Fans	Fan
	Lighting	Lighting
	Freezers	Freezers
		Refrigerator
	Space Heating	Boiler
		Furnace
		Electric Space Heating
	Standby	Standby
	Television	Television
	Water Heating	Water Heater
	Laundry	Clothes Dryers
		Washing Machine

Figure 4: Classification of residential end-use categories according to BUENAS [27]

The remote database table structure links each appliance table not only to a specific *loadclass*, but also to a specific *functionalclass*. The *functionalclass* indicates the main functional category that each appliance is assigned to. Each *loadclass* is assigned to one specific *functionalclass* and each *functionalclass* can contain many *loadclasses*. This association is an example of a one-to-many relationship.

2. *Normalization*

   Normalization is the process of optimising table structures to efficiently organise data in a database. Normalization promotes relational integrity by only storing related data in a table and eliminates the creation of redundant or duplicated data, i.e. when the same data is stored in more than one table [28]. A number of linking tables exist to implement one-to-many and many-to-many relationships. Certain functions are associated with certain occupancy areas and accordingly, only those appliances or *loadclasses* that are grouped within certain *functionalclasses* must be associated. The database design caters for the general case, e.g. a *functionalclass* such as laundry is associated with areas such as a kitchen, scullery, garage or bathroom presupposing that a user will not, under normal conditions, place a washing machine in a dining room for example.

Appliance information

The remote database serves as the repository for efficiency guidelines for the various domestic appliances, information on appliance categorisation, as well as labelling information such manufacturer, brand name, nameplate rating, etc.

Local SQLite database

The local file system

The SQLite database is embedded locally in the application software. SQLite is essentially a flat file system that can be described as follows: "*SQLite is a software library that implements a self-contained, serverless, zero-configuration, transactional database engine.*" [29]. A flat file is defined in the context of a database as a data file that contains records or data with no structured relationships.

Data is stored in a plain text file that contains only basic formatting and each line of the text file holds one record, with fields separated by delimiters, such as commas or tabs [30].

The SQLite database implemented for this application consists of a single database with four tables as shown in Figure 5. The database file sizes are relatively small, i.e. 1 kiloByte (kB) for a comma separated values (csv) file and a few kBs for the entire database file, depending on the extent of a user's areas and load inventories.

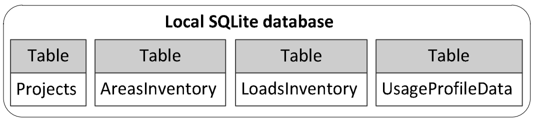


Figure 5: SQLite database structure

The combination of the local SQLite database and AIR's distinctive storage directories, *File.applicationStorageDirectory*, *File.desktopDirectory*, *File.documentsDirectory*, *File.userDirectory* and *File.applicationDirectory*, facilitate production of cross-platform applications without requiring a user to be familiar with the file system of a target operating system [31]. The local database table structures mirror the table structures of the remote database in order to simplify the Structured Query Language (SQL) query syntax. The syntax of MySQL and SQLite queries differ slightly and not all features of the SQLite syntax are supported by Flex and ActionScript [32].

Database management

As an additional support or extension feature, a user may make use of an SQLite database manager such as the *SQLitespeed* manager illustrated in Figure 6. This allows changes to the locally saved database to be performed directly. Other SQLite database administration options also exist, including *phpLiteAdmin* which is a web-based tool written in PHP with support for SQLite2 and SQLite3 [33].

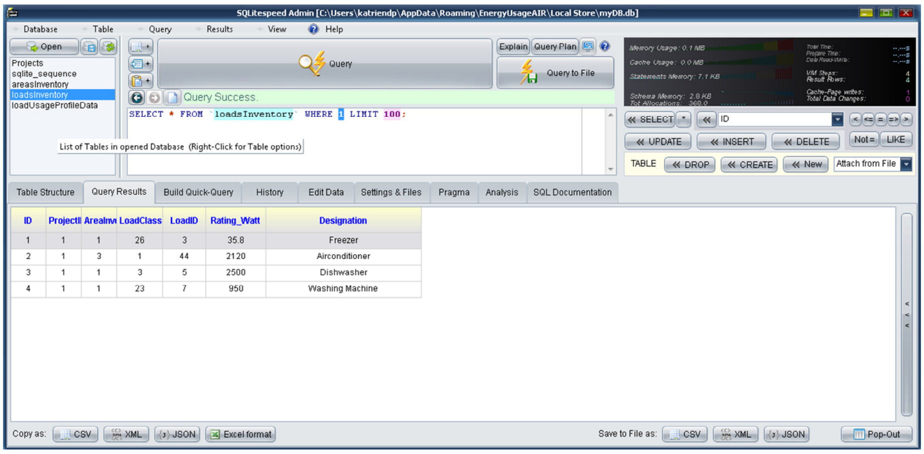


Figure 6: Interface of the SQLite database manager, *SQLitespeed*

Security and permissions

The desktop application is installed by the user and the initial registration process creates a registered user with password protection on the remote database as shown in Figure 7. Access to the remote database is facilitated through an internet connection and a user login procedure. Data binding to User Interface (UI) components ensures real-time data results and updates.

The application is designed to reduce the risk of SQL injections by implementing user selections such as dropdown lists in favour of typed input from the user. Most of the analytical functions, e.g. profile analysis and the creation of graphic displays are performed on the remote server and the results are transferred to the user application. This requires transfer of information between the local database and remote server and execution of complex queries on the remote server. These processes require appropriate permission settings on the remote server.

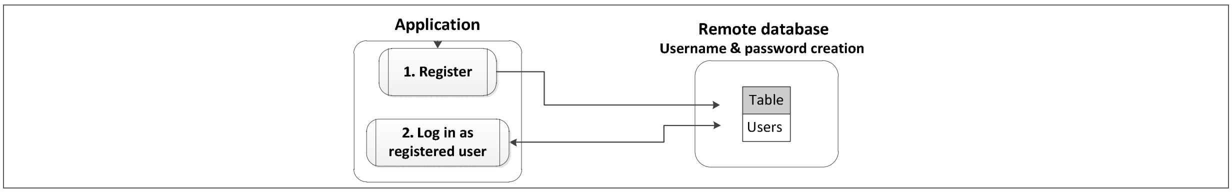


Figure 7: User registration and log in

A beta-release version of the software was deployed on a Linux/Ubuntu server. Ubuntu uses *AppArmor*, a Mandatory Access Control (MAC) system, which is a Linux security module enhancement to confine programs to a limited set of resources [34]. The *AppArmor* security system controls how applications can access the file system. In the case where the MySQL database engine needs to create a file on the remote server, e.g. when executing a user specific query that uses a FILE privilege such as “SELECT ... INTO OUTFILE”, “LOAD DATA INFILE”, or the “LOAD_FILE()” function, the *AppArmor* security policies needs to be addressed [35]. Temporary database tables and files created through user interaction are automatically dropped by the server when the relevant PHP script has been processed or if the session ends.

Analysis tools for interactive data visualization

User interaction requires drag-and-drop actions of graphic icons. Two-dimensional icons are rendered in Flash XML Graphics (FXG) format, which has replaced Scalable Vector Format (SVG). The icon set used in this application represents the occupancy areas and appliances. Apart from the basic component library, custom components were also created for the application.

Custom components

The application incorporates a collection of custom visual components, which were designed to represent appliance data that may be switched on or off. The custom component shown in Figure 8 combines a radio button group with an image, appliance data and required switching functionality.

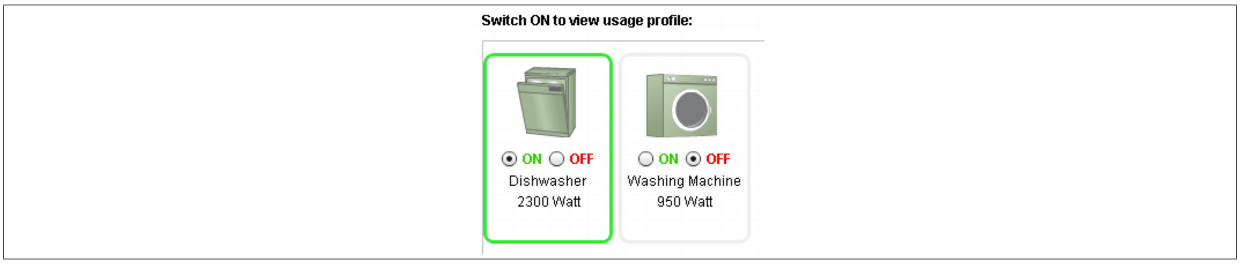


Figure 8: Example of a custom component

Charting components

The following charting components are utilised:

- Native Flex pie and bar/column charts in the analysis section to display installed capacity.
- AnyStock stepline-area charts to display usage profiles. AnyStock charting components are generally used for commercial financial graphing solutions that require the ability to handle large time-stamped data sets. At this stage only the trial version is used, hence a watermark is displayed in the graph. AnyStock is created in Extensible Markup Language (XML) format, which can be included in a PHP script. The charting component consists of two elements:
  - The chart information (wrapper) written in XML format.
  - The data points, given as a csv formatted source file containing timestamp data. The source can be either an external file or a part of the XML settings file [36]. The timestamp format can be specified, e.g. a unix datetime format. The csv source file can be created by the

application, written as the result of a query of the local SQLite database table (*UsageProfileData*), and uploaded to the remote server. Alternatively, the source file may be created by means of a “SELECT INTO OUTFILE” SQL query on the remote server by the same PHP script that renders the chart.

Analytical functions are handled on the remote server side since these involve SQL queries on the remote database to extract the required information. The application copies the content of the user’s *LoadsInventory* table to a flat file (csv), which is uploaded to the remote server where it is accessed and deleted immediately after the relevant query has executed.

As part of the analytical function, the installed capacity indicator is mostly useful in the case of resistive appliances such as kettles, heaters, hot water geysers and incandescent lights that carry a nameplate power rating in Watt [W] or kilowatt [kW]. Due to duty cycle considerations, refrigerators and freezers are characterised in terms of annual consumption values [kWh] provided on the energy label [37]. The interpretation of nameplate rating information is therefor less clear. For these appliances, the power rating values stored as part of appliance information on the remote database are average values calculated using the annual consumption divided by the number of hours per year. In the case of appliances such as dishwashers or washing machines, energy labels will denote consumption information in terms of kWh per cycle [[38], [39]]. When conducting an appliance audit in a home, a user would be able to make a selection based on brand but may not be able to readily use nameplate ratings.

Usage profiles

The usage profile section allows the user to create and view usage profiles. Figure 9 illustrates the data flow required to create and/or view a usage profile. The Unified Modelling Language (UML) use case diagram for the creation of a usage profile is shown in Figure 10:

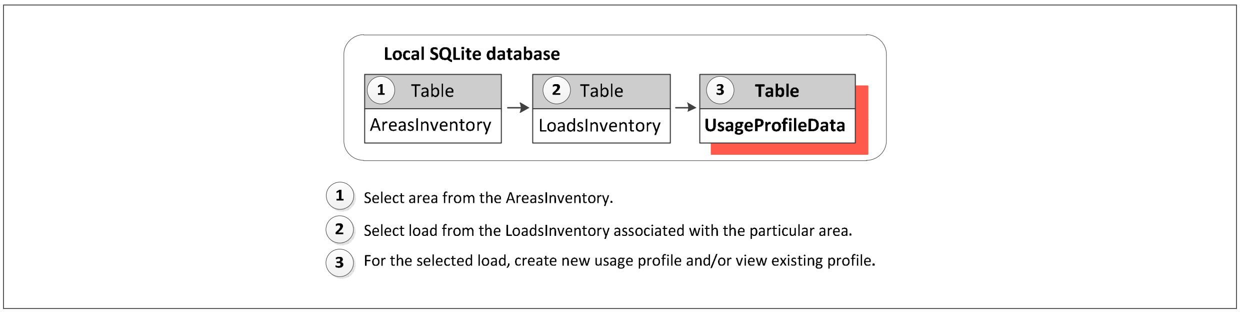


Figure 9: SQLite *UsageProfileData* table to store usage profiles

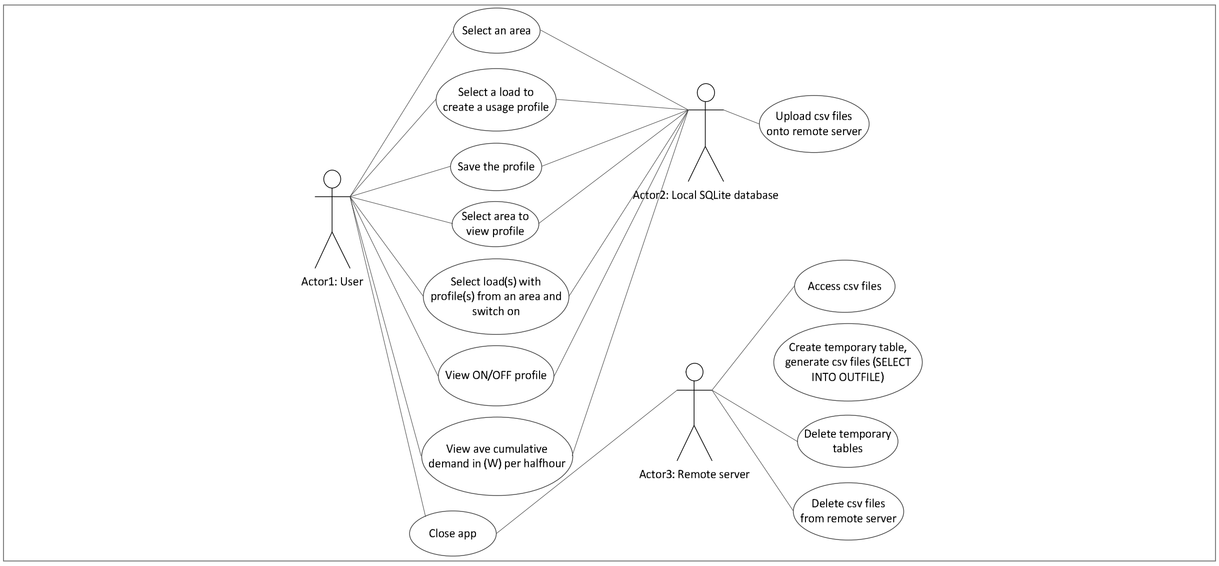


Figure 10: Use case diagram for usage profile creation

Profile types

Usage profiles are represented as a one-to-many relationship in the sense that a usage profile is associated with a particular load although a load may have a number of usage profiles associated with it. A kettle, for instance, may have profiles such as "*Morning coffee for two*", "*Afternoon coffee for one*", etc. and similarly a dishwasher may be used in mornings and evenings. To create a new profile for a particular load in a given area, the user selects the start time and a time of use interval. The switch off time is calculated and the user saves the profile under a descriptive name. An On/Off cycle is generated for each of the loads and written to a csv file. The following profile types are used:

- *On/Off event profiles for one or more appliances:*
  The dashboard presentation shown in Figure 11 displays typical On/Off event times for a user selected range of appliances for a windowed period of 24 hours, divided into 48 half-hourly intervals.

- *Average demand per appliance per half-hourly interval or cumulative demand for an array of appliances:*
  Figure 12 shows an example of the average half-hourly demand [W] for a selection of appliances, derived by combining the average operating times per half-hourly interval with the power ratings of the appliances. M&V data analysis typically makes use of half-hourly interval data to derive energy consumption profiles. Figure 12 shows a view of the half-hourly average demand [W] over a period of 48 half-hour intervals.

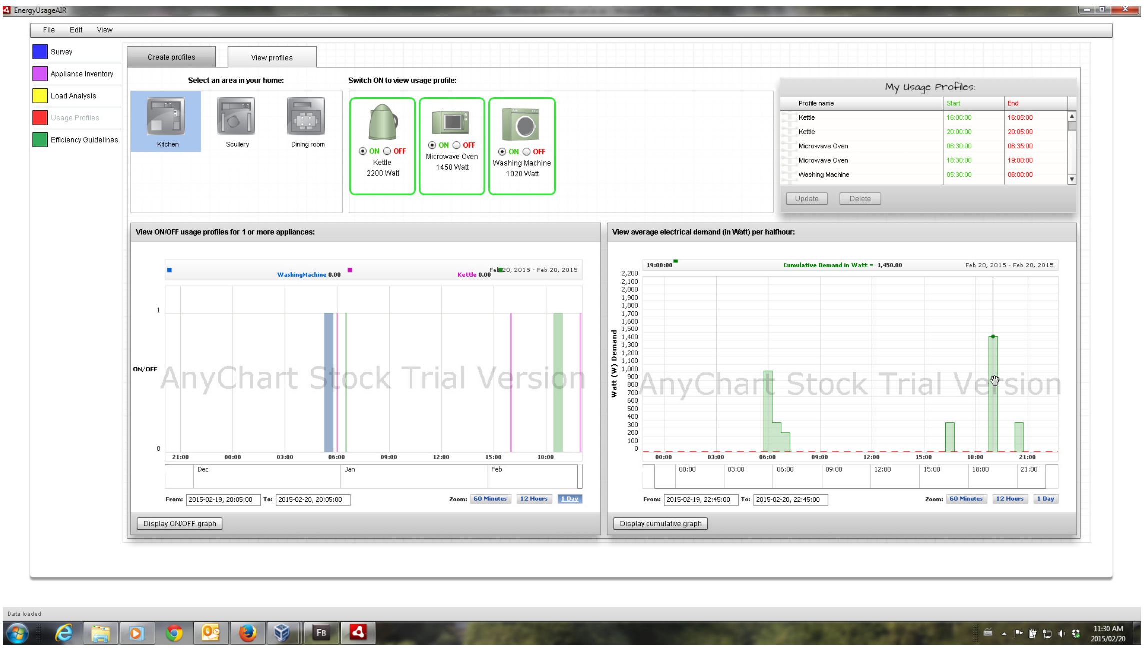


Figure 11: Energy consumption dashboard

Even for a purely resistive and uncontrolled appliance, the actual energy consumption profile may be dependent on external variables that are difficult to quantify. In the case of water heating with a kettle, for instance, the energy consumption depends on variables such as the volume and initial temperature of the water. Average demand usage profiles based on the nameplate rated values are therefore at best only estimates of the actual consumption profile. These values translate to maximum demand for a kettle and, as noted previously, average demand for an appliance such as a refrigerator with annual consumption.

In the case of a complex load such as a washing machine with variable speed drive (VSD) technology, depending on the program selection, a microprocessor controls the start-up profile and the accelerating speed of the motor during washing, rinsing, spinning and drying. Disaggregating continuously variable loads requires measurement and modelling. The capability to integrate duty cycles into a usage profile has not yet been incorporated in the current software version.

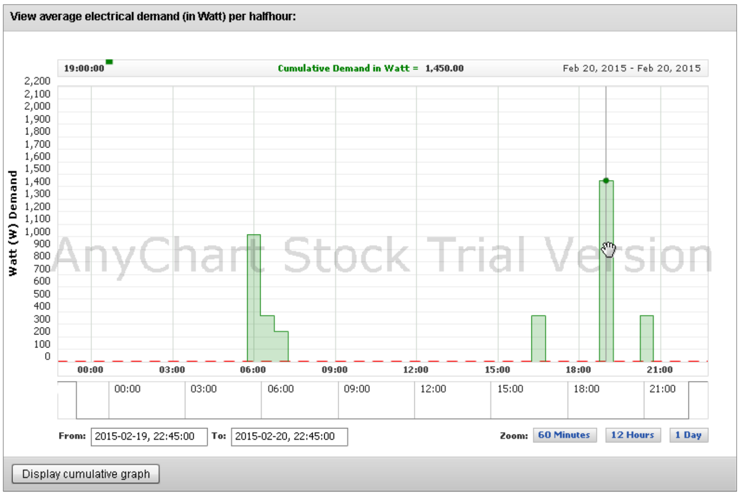


Figure 12: Example of daily average cumulative demand [W] per half hour intervals

Benefits of the proposed application and examples

It may be argued that the useful lifetime of an energy auditing and management tool is limited and that once a user has completed an audit and implemented certain measures to improve energy efficiency, the application has served its purpose, unless there is an incentive for the user to return. The challenge is therefore to ensure persistence of usage and persistence of savings. One such incentive could be continual educational value, e.g. to view regular updates of energy efficiency information and new appliance information that is managed via an updated database. An example of such a tool is the US Environmental Protection Agency's Energy Star programme [40]. This programme is based on a voluntary labelling scheme for consumer products that meet a minimum energy efficiency standard and provides a comprehensive online tool to analyse potential energy savings from various actions at the household level.

Impact of education on energy consumption in residential buildings

Research findings show that smart grid designs should extend beyond technology and recognise that a smart user who is actively engaged with energy is pivotal for Demand Side Management (DSM) [41]. According to the authors, disengaged consumers represent a managed demand side that weaken interventions by requiring limited user involvement. In contrast, an engaged consumer takes on the role of a consumption manager, being involved in both problem and solution, to ensure a more effective response. The authors refer to an "*energy citizen*" as an active participant who can embrace smart grid technologies and act as an agent for change making the most effective smart grid one in which intelligence is sourced from users as well as devices [41].

An appliance database

A centralised database-integrated supply of information promotes a standardised home appliances database framework for energy efficiency and application potential: *"By developing a data standard, this data could be used to feed any number of applications or resources, limited only by what people are willing to design and create.*" [42] An implementation example of such a standard data framework would be a web portal to make available appliance information that is up-to-date with specific current product information [42]. The proposed *EnergyUsageAIR* application's remote database contains a repository of appliance information which could constitute a South African or local implementation of such a framework.

Education through scenario analysis

The proposed application has great potential for the education of end-users on interventions such as replacing inefficient appliances with more efficient ones as well as reducing demand during peak times through load shifting. Consumer education is particularly important in the context of the capacity constraints experienced in South Africa and the extensive use of the *Power Alert* system to induce DR during peak hours. A user's ability to view the result of switching off lights and harvesting daylight instead, or adjusting the timer switch of a swimming pool pump in accordance with seasonal changes, promotes understanding of consumption patterns. The application allows users to model the potential and effect of such EM interventions through built-in data visualization features.

Figure 13, for example, shows how the user can analyse the contributions from various load components to the total installed load rating.

Figure 13 and Figure 14 show how the user can study the load profile of selected loads, e.g. the lighting load and pool pump in this case, allowing for seasonal variations, to gain understanding of the potential for savings in the context of a TOU profile.

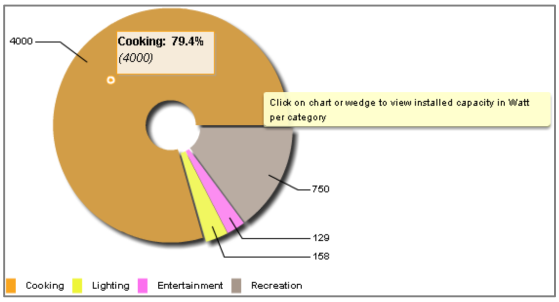


Figure 13: Load analysis view: installed capacity per functional category

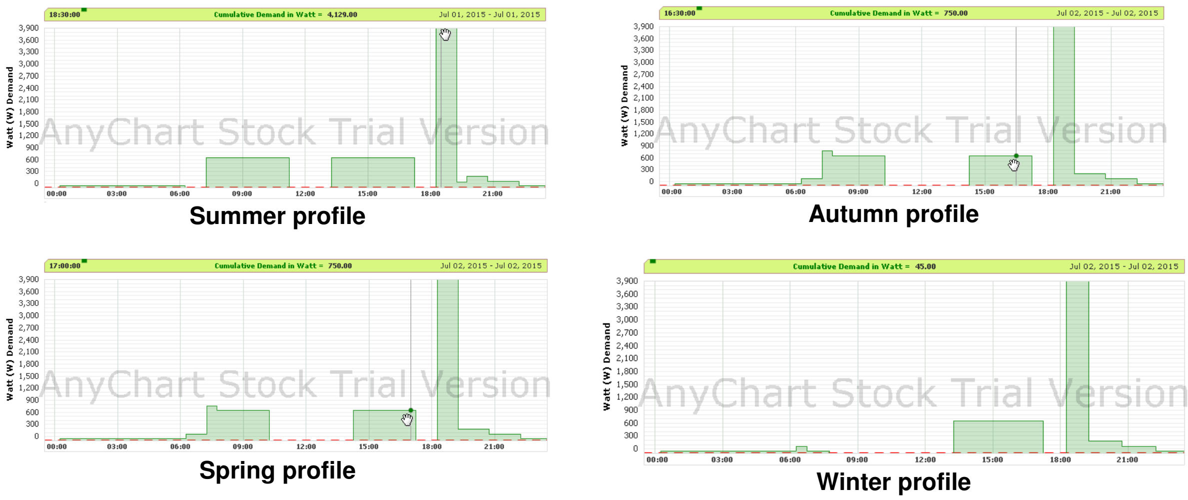


Figure 14: Seasonal daily usage profiles

Conclusions and recommendations

Due to the local electricity supply constraints and the associated load shedding program, the current climate is conducive for capitalizing on opportunities to improve EM and EE in the residential sector. A greater awareness and dialogue has become evident through actions such as the DoE's invitation to participate in solutions. End-users are more aware of consumption and compelled to be pro-active in dealing with the impacts of load shedding.

Recent progress made in terms of S&L in South Africa for domestic appliances represents a positive and important step forward. The education of end-users, however, remains a priority since the correct interpretation of energy label data is dependent on a user's understanding of energy consumption. Consumer education is likewise essential to empower users to reduce household electricity costs in the face of rising tariffs and to respond positively and appropriately to calls for DR interventions on public broadcasting channels. To this end, the software application endeavours to educate users utilising formal M&V concepts such as load auditing, baseline characterization and determining the scope and means for avoided energy use.

Evaluation of the software application as a residential energy auditing tool

An effective residential auditing tool relies on accurate appliance information. This data must be updated regularly on the remote database. This, in turn, is dependent on the availability of data from appliance manufacturers as well as accurate information contained on appliance energy labels. The following problems have become apparent during the development of the application:

- Lack of appliance information. Not all domestic appliances are labelled, especially older models that have been introduced into the market prior to mandatory S&L.
- Correct interpretation of the data on an energy label is subjective in the sense that it is dependent on a user's understanding of energy consumption.
- Interpretation of power rating. Consumers find it difficult to interpret this specification correctly in the case of appliances characterised in terms of annual kWh consumption, such as refrigerators and freezers or cyclic energy consumption, such as dishwashers and washing machines.
- Duty cycle information has not yet been incorporated into the usage profiles for VSD-controlled appliances.

Security and scalability

A hybrid topology utilising both a local and remote database offer a number of advantages:

- Minimising storage space because inventory data can be stored locally instead of on the remote server.
- Reduced risk of compromising data integrity by limiting data transfer between the application and remote server.
- Increased security of user data through locally saved inventories.
- Simplification of the user management system on the remote server.
- Reduced network traffic through the ability to execute queries on the local SQLite database instead of on the remote database.
- Improved scalability since appliance data updates and efficiency guidelines can be performed on the remote database without requiring the user to install a newer version of the software.

Additional benefits are:

- Low initial user data requirements, i.e. occupational areas, load inventories and usage scenarios, in contrast with modelling tools that generally tend to have high initial data requirements.
- The flat file system supports platform portability since the profile data is available in .csv file format, which can be readily imported for use in other modelling applications such as Matlab.

Recommendations

The following recommendations have emerged in evaluating the current version of the application:

- The possibility of offline system configuration and auditing functions should be investigated.
- Energy label information should be included in the remote database as part of the efficiency guidelines section for each appliance.
- The handling and user interaction with specifications such as annual and cyclic consumption data should be improved.
- The inclusion of duty cycle information in the modelling of usage profiles should be investigated.
- The potential of the application for educating school learners through science exposition projects and programs should be explored.

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Demand Response

A Methodology for the Design of Offer Curves in the Future Capacity Markets through Energy Efficiency

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Abstract

The objective of 20% of energy reductions in the European Union by 2020 is far from being achieved. Some reasons can be attributable to a depth economic crisis in the last years and the high capital costs of some efficiency technologies. Due to these facts a conservative attitude of the customer, that induce it to reduce expenses, appeared in the last decade (mainly this fact can be observed in small customer segments which face with considerable barriers to interact with these new technologies and, specially, operate in with energy markets). A possibility to reduce the incertitude with respect to economic payback and thus, to promote energy can be through the revenues achievable by the participation of customers in Capacity Markets. Fortunately, these markets, recently established in the USA (2007/08) or UK (2014), are now open to Demand Response and Energy Efficiency policies. Like in other markets, the participation of the customer needs a minimum level of demand management or its reduction (some hundred of kW) and this is an important barrier to customer engagement. So, this participation needs to perform an aggregation of elemental demands. Moreover, the customer/aggregator needs an easy methodology to build and evaluate energy and cost curves, and estimate achievable revenues through efficiency. The idea of this paper is to show and define a methodology to define the size of energy packages and their monetary value with the final objective of performing offers in Capacity Markets (power reduction) through energy efficiency and taking into account the complementary and possible synergies with Demand Response policies.

1. Introduction: An overview of Capacity Markets

In recent years, the literature addresses the benefits of Capacity Markets (CM) relative to Energy Markets: for the customer a higher payment for availability of its capacity resources; for the System Operator (SO) the increased level of reliability, a reduced volatility, lower investment costs and mitigation of power markets. CM are in expansion in the USA and in the European Union (EU). This work explores, through the use of several simulation tools and tests performed by authors, the definition and evaluation (kW, kWh, economic value) of customer offers into CM. By the use of conventional energy efficiency models, results from pilots (field and laboratory), specific models used in Demand Response (e.g. Physically Based Load Models, PBLM), and some methodologies proposed in the paper (Non-Intrusive Load Monitoring, NILM), the customer and the aggregator can simulate through a basic economic-model the generation of offers in CM when different incentives and penalties are applied. The performance of the proposed model is investigated through a numerical study using CM market data from USA and UK markets.

The objective of capacity schemes worldwide is to provide the power producer enough economic incentives to plan for and develop the necessary capacity (generation and transmission) to meet efficiently the needs of customers during peak demand periods in the long term (the so called resource adequacy problem [1]). Each country, or power system, usually takes a different approach to assure capacity margins and try to solve the adequacy of resources in the long term. Mainly, these schemes are two:

- Price-based mechanisms (commonly known as capacity payments): this involves a central entity that sets a price to be paid for all available capacity. This approach has been usually adopted across European countries in the past (Spain since 1997, Italy since 2004 or UK from 1990 to 2004). The idea is to recognize additional revenues to generators beyond that which they can receive in Energy or Ancillary Services Markets.

- Quantity-based mechanisms: the SO is committed for procuring a certain capacity target that should be made available in a future period (usually 3-5 years). The SO establishes the volume and price of capacity demand, and the actors (supply/demand sides) which plan to add capacity in the future, bid offers for this potential capacity. Some authors [1] classify quantity-based mechanisms according the way in which the capacity is traded: centralized capacity markets (PJM, New England in the USA, Great Britain) or markets with bilateral contracts (Australia since 2005).

The trend is that price-based mechanism is only open to supply-side whereas centralized CM are open to demand-side, i.e. Demand Response (DR), Energy Efficiency (EE) and Distributed Generation. Largely, legislative efforts in the USA [2] and Europe [3, 4] have contributed to the effective participation of demand and supply sides on an equal footing. This does not mean that the supply agents have long discussed the value and, specifically, the retributions of demand resources in some markets (for example, see FERC 745 initiatives in the USA). The mechanisms to stimulate power and demand providers to plan for and develop enough capacity to meet the future needs of the power system (demand) is a challenge for long term planning. The load duration curve (LDC, cumulative load curve, see figure 1 for IESO, Ontario, Canada), and its forecast, usually have conditioned the planning of the power system. The capacity utilization (average vs peak capacity of productive resources, in industrial segments) or the load factor (average vs peak load in power systems) show the same idea: the generation resources of the power system are badly used, in general. For example, table 1 shows some representative examples. The capacity utilization factors in transportation sectors shows that in these segments the demand is quite elastic and is driven by prices, according to resource adequacy.

Table 1. Some examples of Capacity Utilization in economic segments and in power systems (adapted from web sources [5, 6])

Capacity Utilization (%)	Country, sector, year
62.5	USA, Power System, 2009
64	Japan, Power System, 2009
69	Australia, Power System, 2008
76	USA, Manufacturing, 2013
78	USA, Average of Industrial Segment, 2013
85	Germany, Transportation (Air Berlin), 2013
95	Germany, Transportation (DB Schenker, North Rail Freight), 2013

Figure 1 shows, for simplicity, Ontario's LDC for the 10% of peak demand hours. In this example, the highest 10% of the system capacity may be required for as little as 80 hours a year (9% of annual demand in hours), [7]. The power offered during these hours will be paid at high marginal prices in energy markets (sometimes with high volatilities during different years) but there is a general concern in the literature with respect the fact that the revenues received in those peak hours perhaps may not be enough to pay the cost of building and maintain these units. The development of CM increases the revenues (and their stability) for new capacity additions that should be necessary to meet reliability requirements. The consideration of EE policies has the potential to lower the entire duration curve, providing capacity during peak and non peak hours.

For this example, the goal of achieving 5% of demand savings by EE and, moreover, a 10% of DR potential with respect to peak has been considered (these percents of DR & EE potentials have been achieved in some systems of the USA and in several countries of the UE). The number of hours of DR being considered is around 80-160 hours/year. This represents, at least, 40 DR events with 2-4hr of response. The cost of demand-side resources seems to be less costly than new generation. In this case (with EE and DR measures) the load factor is reduced to approximately from 1.6 to 1.38.

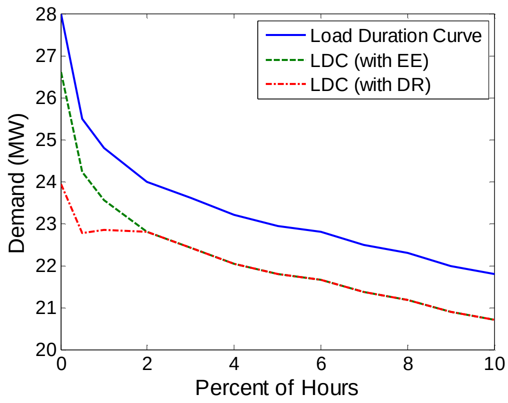


Figure 1. Load Duration Curve (Ontario, Canada, 2012) and the effects of DR&EE policies on this curve (adapted from [7]).

The remaining of the paper is organized as follows. In section 2 a review of rules and procedures for the participation of customer in CM markets with emphasis on EE policies is briefly discussed. In section 3, physical models and tools to forecast the change in power and demand due to different EE policies are revisited and discussed. Section 4 is devoted to describe a model which includes technical and economic parameters to perform numerical simulations and studies considering different scenarios for market price, incentives and penalties, and shows some basics results of the sensitivity of each offer with respect to some inputs. Finally, section 5 concludes the paper.

2. Rules and procedures for the participation of Energy Efficiency in Capacity Markets

The qualification of resources and bidding rules in CM were initially proposed for supply-side resources only. However, the decision to allow the participation of demand-side resources implies the necessity to create rules and procedures adapted to the different characteristics of each resource. CM markets in PJM and ISO-NE (USA) have developed some rules that condition how EE&DR can participate in their markets. Similar rules are forecasted in future for the European CMs. For example, the end-user (and the aggregator, of course) should take into account:

– Peak period for measures: time of the day and season considered as peak periods. For example, ISO-NE defines its peak period from 1 to 5 p.m. on summer weekdays (but the resources are required to meet winter requirements too) whereas PJM focuses only on summer peak period.

– The types of policies that can participate: almost any policy that generates savings at the time of interest for the SO. For example, retrofitting devices: efficient lighting technologies, new appliances (heat pump water heater), heating/cooling equipment (electronic inverters), electronic drives for motors, building weatherization (envelope improvement), …, can bid into the market. According to PJM manuals, some policies does not meet definition if the new devices do not improve standards/baselines, the demand is reduced by a change of behavior, or the user switches an appliance or process from electric to gas. The inductor for EE: usually in CMs there is not distinction made between program induced efficiency (utility, regulator, local governments,…) and "free riders". There are not requirements to demonstrate that the savings achieved were additional, i.e. what is commonly termed "additionality" in EU.

– Operational lifetime of EE policies: This point is crucial in consumer participation in CM because the income forecast depends largely on the decision whether or not new investments in efficiency. The framework is quite different in each specific market. The policy of ISO-NE is that its customers receive payment for cleared EE projects during the full expected operative life of the measure (5, 10 or 20 years), whereas customers in PJM only receive the qualification of capacity resource (and the revenues associated) for a maximum of four years.

- Aggregation: A minimum resource size is usually required in CM markets. In UK the minimum proposed size is 2MW whereas PJM and ISO-NE allow a minimum size of 100 kW for bidding. It is not possible to aggregate resources from different zones or control areas in the power system.

- Qualification: the sponsors of EE projects should submit documentation to SO to justify the policies to be used for energy savings. For example, a forecast of the peak saving capacity, the cost and capacity to acquire or manage resources, and a measurement and verification plan (M&V) to validate the savings. This last point is the most important one for the SO and the aggregator/customer. The EE “supplier” must demonstrate that their resource is reliable and will accomplish savings at the times considered as peak periods by SO. For these M&V plans, it is necessary to know a baseline and then to propose a method that involves the analysis of the impact of an EE measure (comparisons of changes in energy bills, multivariate regression analysis or simulation models and tools such as those proposed in the paper, to replicate old and new end-use demands).

- Credit requirements, payments and penalties: resources cleared in the market are paid at the clearing price for the year in question. The pacer of payments can be monthly or weekly. Figure 2 shows the evolution of CM prices per kW and month in PJM and ISO-NE markets [8]. Finally, it is important to take into account the requirements and penalties for non-compliance in each market.

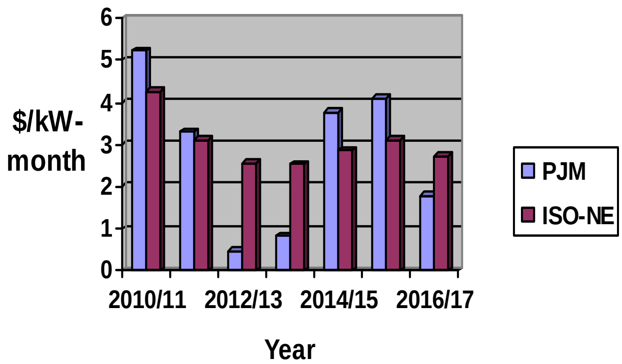


Figure 2. Resource clearing prices in PJM and ISO-NE markets

2.1. Participation of Energy Efficiency and Demand Resources in Capacity Markets: Some results to date

UK Capacity Market: The CM market auction results for 2018/19 were announced last December. Two facts are remarkable for this first action: the prices were less than expected (£19.4/kW-year) and the volume of DR cleared (DSR is the denomination in UK markets), only 172MW from DR were accepted. Bids from aggregators such as Kiwi Power Limited and EnerNOC UK (452MW) were unsuccessful. In total, DR accounts for about 0.35% of the total successful volume, i.e. around 49.25GW [9]

ISO New England (USA): The overall participation of EE measures in this CM (Forward Capacity Market) have almost tripled over the past eight years (from 650MW in FCA1 auction in 2008 to 1820MW in FCA8 in 2013). The amount of 1.8GW of EE that was cleared in last cassation represents a half of the DR resources, but only a 4.3% of the total capacity (however, this represents more than 10 times the percentage achieved in UK). It is important to stress that most of EE resources were bid into the market by electric utilities and almost all of the rest by what ISO-NE (and literature) calls “quasi-government” institutions (entities that are driven by local government policy to invest in efficiency and therefore have other sources of revenue, i.e. stronger economic incentives that capacity payments). Notice that almost none of the EE resources came from ESCOs or aggregators. According to some reports [8] the net CM revenues represent about 10% of the capital cost of resources being acquired. That revenue is far to fully support EE measures but is a catalyzer to augment efficiency efforts.

PJM (USA): PJM customers face to more barriers in CM. The first is that PJM only allows revenues in the first four years of savings. Perhaps for this reason EE represents about 8% of DR resources and

0.64% of the total capacity cleared in CM. However, the trend of the participation of EE resources in this market is largely positive, having been folded in recent years from 569MW to just over 1200MW.

3. Qualification of EE policies: measurement, verification and simulation

As stated in section 2, an important element for qualification in CM markets is the measurement and verification plan. It is also important to define one of the main characteristic of the bid in the CM markets (mainly the savings in demand and consequently the energy and the time where both occur which should match the peak of the system, i.e. the qualification process mentioned in section 2). To evaluate these offers from an energy point of view, the customer and aggregator have several options and some of them are explained in the next paragraphs. All of these possibilities have been used for building energy blocks in section 4 (energy packages) to improve the usefulness of the model for the reader. Some tools come from EE literature and manuals whereas others are tools being developed by authors for the evaluation of DR policies. In this way, common tools can be developed and used in DR&EE, promoting the synergies of demand-side resources and reducing the complexity of CM markets for the aggregator and customers.

3.1. Engineering simulation models

This method involves the use of simulation models, for example Physically Based Load Models (PBLM) used for DR evaluation and simulation, in which the models simulate physical laws of the load and its environment (heat gains, heat losses, heat generation, heat storage, water or process flows, etc) to determine the load behavior and then the model is calibrated (through real data measurements) to replicate actual or future energy usages. The advantage of these models (a detailed explanation about formulation and the physical meaning of the parameters of the model can be found in [10], [11]) is that they can replicate the effect of a non-electrical variable (e.g. in heating/cooling end-uses, which are the effects of roof and floor insulation, window glazing envelope replacement or wall insulation, etc) or to estimate of demand and energy savings in new construction projects.

This section uses a PBLM model for residential heating/cooling devices that involves the development of an equivalent model (RC network) that represents the energy balance between an appliance/load, the dwelling where the load renders the service (indoor) and the environment. Figure 3 shows a model for a HVAC unit [10] prepared by authors for the European Research Project "EU-DEEP "[12].

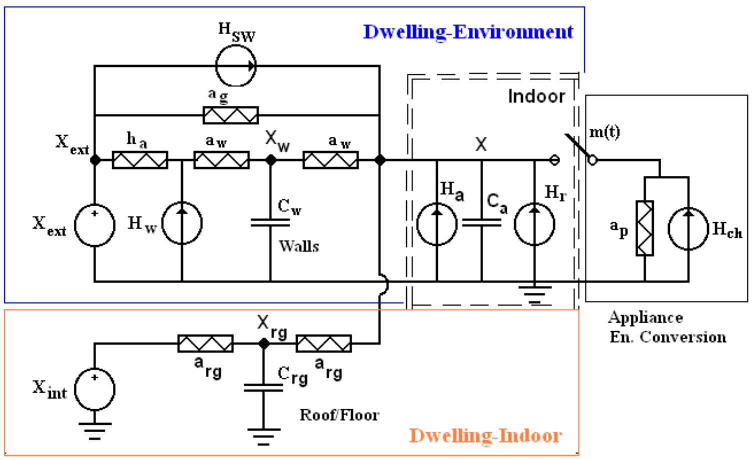


Figure 3. PBLM for residential heating/cooling loads ([10], [11]).

The effect of improving the thermal transmittance of windows is considered with this approach. In the base case (baseline), the thermal transmittance coefficient (the so called U-value) is 2.3W/m^{2}K. The objective is to evaluate the efficiency gains due to the replacement of the glazing envelopes with a new window with a value of U around 1.3-1.4 2.3W/m^{2}K. This parameter (thermal losses or gains through glazing envelope) is represented by "ag" conductance in PBLM. Figure 4.a shows the effect in losses through the windows, whereas figure 4.b. shows the change of switching on/off rate of the appliance (1800W of rated power). This behavior is needed to compute the power reduction in the customer side (aggregated/individual loads) to compute CM offers (see section 4). Table 2 shows some numerical results for these policies.

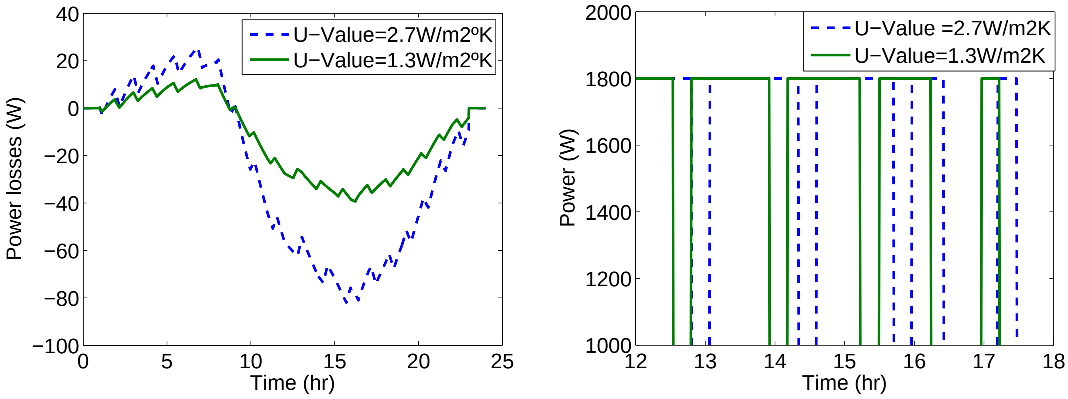


Figure 4. a) Change in heat losses through glazing surfaces due to windows replacement; b) The change in demand for an individual appliance at power system peak

Table 2. Some numerical results for residential dwelling insulation policies in figure 4.

U factor ($W/hm^2 ºK$)	Power (kW)	Daily demand (kWh/day)	∆Demand (kW, PBLM model)	Savings (kWh/yr credits according to [13])	Incentives e.g. Ireland (€)	Incentives e.g. USA [14] ($)
2.7	1.29	17.94	-	-	-	-
1.3	1.25	17.58	-0.36	1050	39.20	20

3.2. Energy audits

Audits are another way to evaluate energy savings when it is possible from technical and economic points of view. In some cases, when the technology is not in its full maturity, the development a pilot project is of the maximum interest to avoid unnecessary risks in EE investments. These pilot projects can provide both customer and aggregator, valuable information applicable in the future in the replication of DR&EE policies in other customer segments. In this case, the energy database deals with the retrofitting of lighting technologies in an institutional customer: the classrooms of a University. According to the last trends (and regulations, of course), dimmable ballasts, the consideration of daylight (through the use of photo sensors and dimmable ballasts) and “revisited” technologies, such are induction lamps, were evaluated in a real pilot (EU programme Greenlight [15]).

These pilots are of interest for two reasons: first, the baselines for some customers are far from an average behavior considered in other methods (for example, in our case the illuminating baseline level for a classroom shown in figure 5a); second, sometimes the performance of new technologies is not well known and it needs to be evaluate on site (induction lamps for the same figure). In the case shown in figure 5.b the change from HID to induction lamps shows around 50% of savings and the reason can be found in figure 6. This shows the demand of two 165W induction lamps. After 45-60 minutes from switching-on, the demand of the lamps falls down to around 100W in steady state (35% of savings with respect to the rated power of the lamp). The illuminance levels in figure 6b show that in some dwellings the illuminating levels were wrong considered in its original design (levels around 500-750 lux are quite good for this end-use) and so, some bulbs can be removed (4 lamps in this example).

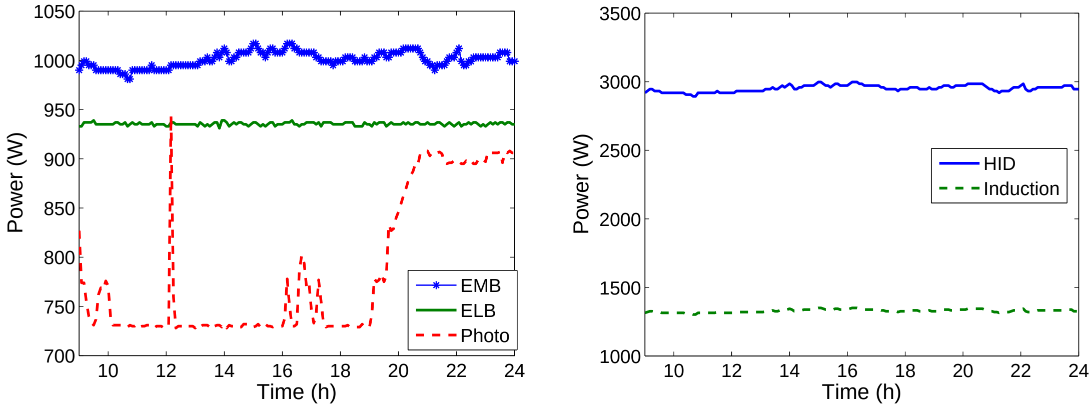
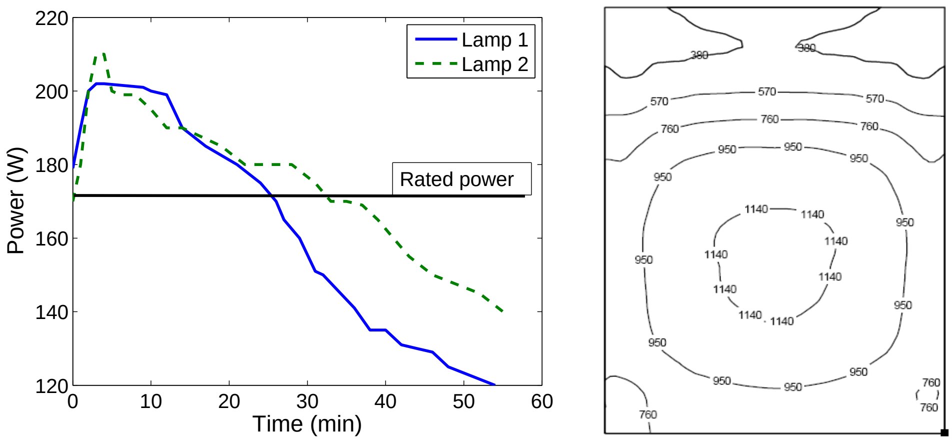


Figure 5. Energy audits in lighting projects (month: July): a) The evaluation of the change of magnetic ballast (EMB) with electronic ballasts (ELB), or with dimmable ballast and photo sensor (photo); b) Retrofitting of HID metal-halide lamps (150W) with induction lamps (165W).



a

b

Figure 6. Lighting retrofit: a) Dynamic response of 165W Induction Lamps; b) Illuminance level curves (baseline, in lux) for the classroom considered in figure 4b

The numerical results or these policies are shown in table 3. These results will be applied later in our model to perform bids in CM markets.

Table 3. Some numerical results for institutional lighting retrofit policies ([11])

Policy	**Power (kW)**	**Daily demand (kWh/day)**	**ΔDemand (kW/day, audit)**	**ΔDemand (%)**	**Savings (kWh/day)**	**Incentives e.g. USA [14,16] ($)**
T8 baseline (EMB)	1.045	15.02	-	-	-	-
T8. Electronic ballast (ELB)	0.92	13.99	0.125	-5.86	1.03	-
T8. Dimmable ballast (Photo)	0.78	11.78	0.265	-26.01	3.24	$25+

HID (baseline)	3.63	44.27	-	-	-	-
Induction	1.674	19.93	1.626	-54	24.34	$25/fixture
T8 LED (*)	0.396	5.692	0.649	-62.1	9.33	$10-20/lamp

(*): Considered in 2015 as a pilot for some meeting-room and laboratory

3.3 Measure savings algorithms

It is usual that some energy saving manuals [17], [18] provide formulas and default assumptions for estimating energy and impacts on peaks due to EE measures and programs. They are promoted by regulators, public laboratories or the so called "quasi-governmental" institutions. These algorithms allow, for each measure, calculate gross customer electric savings but without counting the effects of line losses or freeridership. Also, they do not distribute the savings among the different cost periods (this is an important drawback for a precise evaluation of savings, but provide a first estimation for pre-feasibility studies of EE policies). Its main interest is for residential customers where energy audits are more difficult if statistical aggregation procedures are not considered. For instance, NREL (USA, [18]) defines equation (1) for residential lighting:

$$kWh_{saved} = NUMMEAS * (\Delta W / 1000) * HRS * ISR * INTEF \quad (1)$$

where: kWh_{saved} is first year electricity savings measured in kWh; NUMMEAS: number of measures sold or distributed through the program; ΔW: baseline wattage minus efficient lighting products wattage in W; HRS: annual operating hours; ISR: in service rate (i.e. the percentage of incented products that are ultimately installed by program participants), and INTEF: cooling and heating interactive effects

Some of these organizations [13], [19] include excel based software to perform a rough analysis of EE measures, but as stated in previous paragraphs, they use standard/mean values. For example, SEAI web (Ireland, [14]) includes tools for the analysis of tubular fluorescent lighting and control measures. This software uses a savings parameter of 0.17 for occupancy sensors, i.e. considerably less than the one obtained in the pilot (see table 3). This can involve errors in the evaluation of CM offers.

The EE measure considered in this case is the change of incandescent bulbs with CFL or LED lamps. The second option has the additional advantage of apply subsidies in some countries with the aim of promoting LED technologies. For evaluation through equation (1) or similar, the NUMMEAS parameter (number of measures sold or distributed) is obtained from Spanish and EU databases. According to SECH-SPAHOUSEC project ([19]) the number of lamps per house in Spain is 23 (3 lamps in each room). The penetration of CFL lamps in the residential sector in Spain is 7 lamps per household but GLS lamps are the most common and (8.6 lamps/household), moreover, the penetration of LED technologies are far from an optimum. The CFL penetration can be explained through the Action Plan 2008-2012 of the Spanish Government (a plan to retrofit 34 million of lamps by CFL). This involves 2 new lamps per house. Taking into account these premises, it seems that the retrofit of 2 new lamps per house is a good estimation for NUMMEAS.

HRS represents the estimated hours per year that the energy-efficient lighting product will be used. Recent studies have shown a wide range of estimated HRS for CFLs, from a low of 1.5 to a high of 2.98 hours per day [17]. This data is important to evaluate demand reductions. With respect to ISR, it is more complicated its evaluation. Some authors use a range from 70% to 90% [17]. Due to the fact that the proposed measure can be considered very conservative, ISR=100% has been considered.

Moreover, the estimated energy demand for lighting in Spain is 450kWh/year-house [20]. The change of two incandescent (GLS) lamps with an intensive end-use (10% of end-use demand) involves savings around 75- 80% (LED or CFL) giving average savings of 28 kWh/year-house and 0.025kW/house (here a value of 3 for HSR has been considered).

With respect to the estimation of demand and energy savings (see table 3), the proposal is to use a lumen or wattage equivalency approach. Both parameters are included in EU, USA and manufacturer energy labels, and the customer usually uses this information. In the case of 60W GLS lamps, the replacement option is 15W for CLF and 11W for LED lamp.

Table 3. Some numerical results for residential lighting retrofit policies

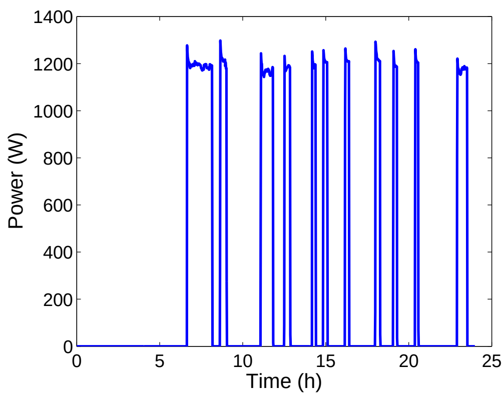
Policy	Power (kW)	Daily demand (kWh/day)	ΔDemand (kW/day, algorithm)	ΔDemand (%)	Savings (kWh/day)	Incentives e.g. USA [15] ($)
2*CFL replacement	2*15=30	0.045	0.045	-38	0.072	50% (*)
2*LED replacement	2*11=22	0.033	0.049	-41	0.084	$10

(*): Replacement of 5 or more lamps.

3.4. Non Intrusive Load Monitoring (NILM) for the evaluation and verification processes

According to the literature [19], one objective of NILM is to find load signatures for end-uses on aggregated demand data (see literature reports in the USA and the EU [21], [22]). For this study, a new tool based on the Hilbert Transform is used herein to identify and characterize the more suitable loads for DR&EE measures. Main characteristics such as cycling frequency, power level and pulse width can be identified from aggregated data [23].

Figure 7a shows actual "natural/own" duty cycles for an electrical water heater (capacity: 100l). Figure 7b shows the daily-demand waveform for a residential customer living in a block of flats in the Southeast of Spain, recorded by a low price smart meter (price < €150, internal pacer triggering < 1 sample/min, input channels: voltage, current and P&Q powers, data storage capacity around 1GB). It is not trivial to identify end uses while WH works at the same time as other loads. Figures 7c&7d show the disaggregation of water heater (WH) and electric heating (EH) end-uses (in this case, their duty cycles). Notice that cycle of EH changes due to its response to a DR control signal during a peak of the system (see figure 7d). With this methodology the aggregator can perform the estimation of the suitability of WH in the times considered by SO as peak periods for CM, whereas at the same time evaluates the DR potential for other end-uses.



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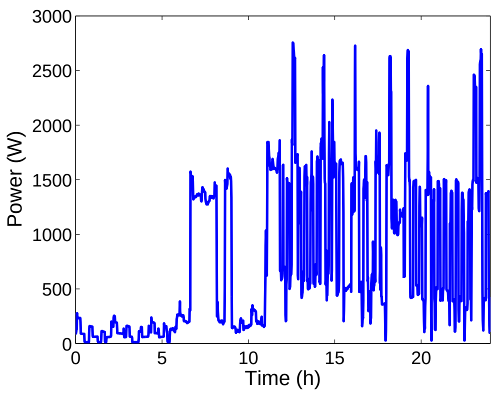

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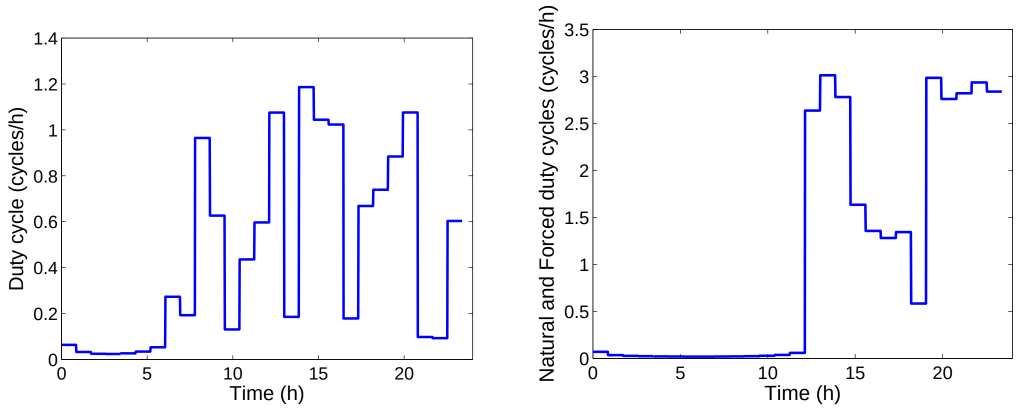


c **d**

Figure 7. Application of NILM for Evaluation and Verification tasks. a) Water Heater End-Use (monitored); b) Overall demand of a residential customer; c) Water Heater behavior (estimated by [22]); d) Electric heat space end-use under DR policy from 14h to 19h (estimated by [22])

According to figure 7c and the duration of ON cycles obtained through NILM (the procedure is presented in detail in [22]) the average demand from 13 to 18h is 0.146kW. The EE policy under study is the substitution of a conventional WH by a Heat Pump Water Heater (HPWH). This load grows in popularity in the USA due to its performance (energy efficiency, COP > 2), but the price is an important drawback (federal and utility subsidies are proposed for the customer). For simulation, the efficiency characteristics of a GeoSpring HPWH (capacity 200 liters and manufactured by General Electric, [23]) have been used but through NILM pattern and the normalization of size and customer service (l/day, see table 4). The price of this appliance ranges from \$1060 to \$1800 in the USA.

Table 4. Some numerical results for residential HPWH

Policy	**Power (kW)**	**Daily demand (kWh/day)**	**ΔDemand (kW/day, algorithm)**	**ΔDemand (%)**	**Savings (kWh/day)**	**Incentives e.g. USA [16] (\$)**
WH Baseline	0.146	2.38	-	-	-	-
HPWH	0.073	1.19	0.073	- 50	1.19	500

4. Energy packages for EE offers

It is necessary, in order to fully describe the offers resulting from EE (and DR) for the participation in CM markets, to determine the involved costs and revenues, so that the price for these offers can be set up. The gross value of each kW package (€/kW-year) to be offered in CM markets can be obtained for a pre-feasibility study (for simplicity, without taking into account escalation rates and considering that the customer has own founds enough) by the equation (2):

$$Offer = \left[\left(CA + IC * cic + \sum_{k}(ICT_k * citc_k) - INC + AGG * life\right) - \left(\sum_{i=1}^{life}(ENER * price_i) + AIC + OM * life\right)\right]\frac{1}{PWR * cmyears} \qquad (2)$$

This expression is based in the consideration of the parameters presented in table 5.

Table 5. Description of items being considered for the evaluation of packages

Cost/revenue	Short name	Description
Initial costs	CA	This category include costs for purchasing the energy equipment and costs for any other miscellaneous items
Installing costs	IC	costs for installing the EE equipment
Avoided installing costs	AIC	The avoided cost for installing the baseline equipment during the lifespan of EE measures
Installing coefficient	cic (binary)	I t includes installing the energy equipment. If the old appliance/equipment has reach the end of its lifespan or lifetime, the coefficient is 0, otherwise is 1.
O&M	OM, (annual)	Operation and maintenance of EE measures
∆Energy	ENER (annual)	The savings on energy due to the EE policy
∆Power	PWR	demand reduction due to EE or DR policies
Incentives, subsidies	INC	the EE&DR measure has some revenue from utilities or governmental authorities, see for example [14], [16].
CM clearing prices	cmr	the revenues if the offer has been cleared in CM
Operational lifetime in CM	cmyears	The number of years that a Demand-Side policy receives the qualification of “capacity resource” into the markets.
Lifespan	life	The operational life of the appliance/equipment
Retail price of electricity	price	the price of electricity €/kWh (*)
ICT costs	ICT	The cost of monitoring, control and communication from the aggregator to the customer and vice versa
ICT cost coefficient	cict (0-1)	Some control and monitoring equipment (e.g dimmable ballast) and its cost can be shared by DR and EE policies
Financial costs	FIN (annual)	In some cases, the debt interest rate (%), which is the annual rate of interest paid to the debt holder at the end of each year.
Aggregator management	AGG (annual)	It summarises the estimated costs associated with ensuring that the project is managed as designed

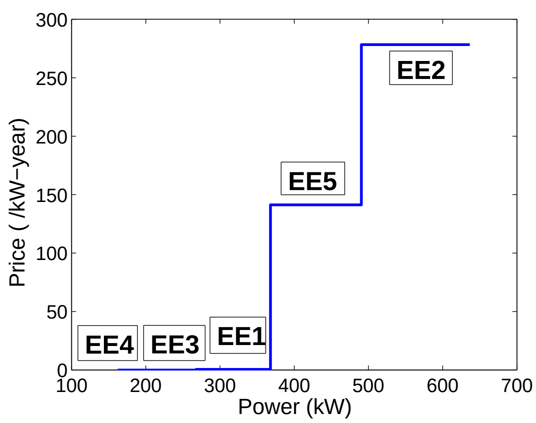
(*): The model escalates the retail price of electricity yearly according to the energy cost escalation rate starting from year 1 and throughout the project life.

To determine the size of packages it is considered that the aggregator manages 5000 residential and 40 institutional customers in Spain. For simulation purposes, incentives and CM clearing prices in the USA and UE have been considered in some cases [13], [16]. Table 6 shows two of the results of equation (2) with respect to demand savings (kW offered) for EE policies considered in section 3.

Table 6. The reduction of demand achieved for the overall group (5000 residential + 40 institutional) due to EE portfolio. Characteristics of policies are defined in section 3.

EE policy	Customer segment	Customer engagement	∆P (kW)	Price (€/kW-year). Fig 8a	Price (€/kW-year). Fig 8b
EE1: Dwelling insulation (windows)	Residential	50%	100	0.5	2.5
EE2: HPWH	Residential	40%	146	278	695
EE3:Dimmable ballasts	Institutional	100%	106	<0	< 0
EE4: Induction lamps	Institutional	25%	162	<0	< 0
EE5: LED	Residential	50%	245	141	530

Figure 8 shows four examples of offer curves taking into account different possibilities and values for items in table 5. For instance, figures 8a&8b present a case in where our aggregator (and its customers) faces to a lack of incentives (subsidies) for EE1-5 policies. Figure 8a considers that CM market gives payments for cleared EE projects during the full operative life of the measure (cmyears=life): this is the actual case of ISO-NE (USA). Figure 8b considers that revenues are limited for a maximum of 4 years (the case of PJM, USA). According to actual clearing prices for both markets (see figure 2), the result is than EE3 and EE4 policies are cost effective without CM markets; EE1 will be cleared in markets (according to ISO-NE and PJM prices, around 25-30€/kWh-year), but EE2 and EE5 can not be considered as a capacity resource in these CM markets. In the case of EE2, if some incentive is considered (e.g. above €150 from governmental authorities [16]) EE2 can be accepted in CM (see figure 8c). Other variables of interest are energy price (parameter price) and capital cost of EE alternatives. In the first case, price forecasting is also of interest for DR and some additional tool [24] can be use to refine the price of offers and some risks. In our case, an increase of 20% in retail price has been considered in figure 8d: EE2 reduces its offer price considerably and now it is more interesting for the customer than EE1 (energy savings decide customer income). Moreover, the possibility of a high penetration of a technology (due to lower prices and market share of the technology) reduces the value of the offer: this is the case of EE5 when initial costs (CA) fall by 50%. These results show that the values of "EE offers" present a high volatility depending of a lot of parameters. These models can help to refine the offers in the future CM.



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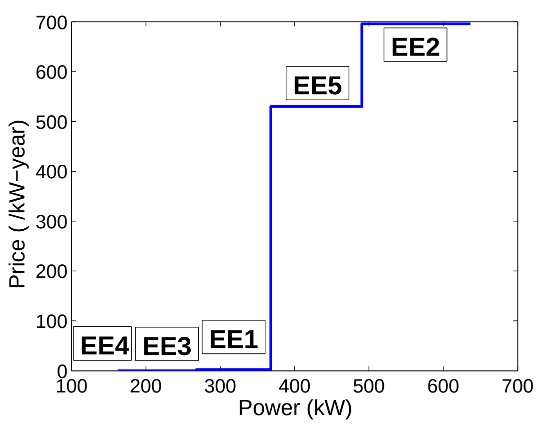

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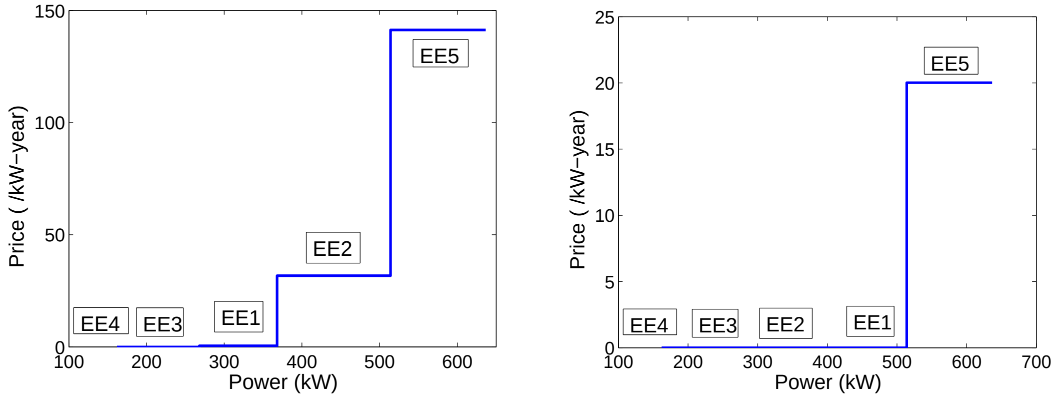

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Figure 8. Price vs. Power offer curve: a) Offers in a market with revenues during all the lifetime of EE policy; b) Offers where the qualification of EE measures is limited in time; c) Effect of incentives in EE2; d) Effects of retail price and the change of capital cost of EE measures.

5. Conclusions

The right operation of electricity markets is quite doubtful without the active participation of the demand-side. A methodology to perform CM offers, suitable for customers, with or without an aggregator, is presented in this work. The participation of customers in CM has several advantages. From the technical point of view Demand-side resources can be cheapest and more reliable than supply-side alternatives and these are advantages for achieving the integration of new renewable resources by 2050 and, in this way, defer the addition of new resources to cover transmission and distribution system peaks. From the point of view of the customer and the aggregator, the requirements of CM have aroused the interest for developing more detailed studies and tools for different EE and DR policies targeting to a larger number of demand segments. These studies should enrich the understanding of both customers and regulators in the understanding of EE efficiency drivers. For this purpose, a discussion of the main elements of the model (the evaluation of demand, power reductions and the monetization of load service) which drives and simulates EE participation in CM is presented in the paper. Another important issue proposed in this work is how common tools developed for DR and EE can be used in the future by aggregators to simplify and improve the participation of demand-side into the markets.

6. Acknowledgment

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Developing a modelling framework to quantify the demand response potential of domestic appliances in UK homes

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Abstract

Smart Appliances will allow households to time-shift certain energy demands enabling better matching of demand and supply as a key part of a smart grid. There is only limited evidence that quantifies this potential and previous studies have focused on a small number of appliance types and only in peak periods. To address this research gap, this paper presents a modelling framework that generates realistic electricity demand profiles for domestic appliance use that are based on measured data. The aim is to use the model to provide insights into the amount of flexible demand that can be available for shifting, when aggregated across a number of homes.

A bottom-up modelling approach is taken which is based on measurements of domestic appliances such as switch-on times, operating time (duration), respective power consumption and frequency of use. The method of the framework uses a probabilistic approach, where probabilistic functions representing the likelihood of appliance usage are constructed and then used to generate high temporal resolution, end-use specific household electricity demand profiles that represent random variations between individual homes.

This paper shows the initial analysis of demand shifting of washing machines with automated response as an example to quantify the potential of demand response for 100 households. The results indicate that a mean power demand between 1 W to 15 W (from 50 W mean power peak demand in the morning) is found available for shifting due to washing machines which provides a useful contribution for demand-supply balancing strategies.

Introduction

The UK electricity sector will undergo a significant change as part of the transition to a low-carbon economy over the coming decades (DECC, 2014a). Traditionally, conventional power plants follow the demand which is the sum of the requirements of all consumers connected to the power grid. These power plants are called upon to generate electricity according to foreseeable demand fluctuations. However, demand-supply balancing in electricity grids becomes a more complex problem by the increased time-varying and less controllable supply side due to the increasing share of intermittent renewable electricity generation. Due to intermittency, renewable power may not be able to contribute towards meeting the peak demands (McKenna, 2013). Additionally, renewable power generation fluctuations may happen quite rapidly due to change in meteorological conditions, disturbing the stability of the frequency of electricity. Challenges for system balancing also arise as the grid becomes overloaded by the renewable power with not enough demand on the system to make use of it. For instance, the surplus electricity from solar photovoltaics can potentially increase the voltage of the local electricity distribution system beyond the regulated voltage level and utilities may need to install expensive voltage regulating devices (Fujimoto et al. 2011). Demand flexibility, in particular demand response, is increasingly recognized as part of the system to help to tackle these challenges of demand supply balancing (Fischer 2008, National Grid, 2009; Ofgem, 2010; IEA, 2011). Smart appliances will allow households to time-shift certain electricity demands enabling better matching of demand and supply as a key part of a smart grid. An approach is needed to quantify the potential of time shifting electricity demands in the UK residential sector.

The aim of this work is to develop a modelling framework that generates electricity demand profiles for domestic appliance use in order to quantify the demand response potential of domestic appliances in UK homes. Such a model can be used quantify the amount of flexible demand that could be shifted, when aggregated across a number of homes. There is only limited evidence that quantifies this potential and previous studies have focused on a small number of appliance types and only in peak periods (Paatero and Lunds, 2006; Fujimoto et al., 2011). To begin to address this research gap, 100 homes are simulated and the modelling framework provides the shifting of washing machine to show how much electricity demand can be shifted during different hours of a day, outside of the times of peak loads. This method will allow study other appliances for demand shifting. The results will be of interest to electric distribution utilities and system operators who need to balance demand and supply in low carbon systems and integrate dynamic pricing tariffs into organized wholesale markets

Methodology

Two modelling approaches for household electricity consumption can be identified: top-down and bottom-up (Swan and Ugursal, 2009). The top-down modelling approaches regress or apply factors that affect consumption to attribute energy consumption characteristics of the residential sector (Baltagi, 2002; Muratori et al. 2013). These models are not concerned with individual end-uses. On the contrary, bottom-up modelling approach calculates the energy consumption of an individual or group of households by identifying the contribution of each end-use to the aggregate energy consumption. Modelling demand on a bottom-up basis allows user to modify and extend the simulations using the components of the model to evaluate the impact of different appliances, future technologies and different usage patterns as high level of detail (Capasso et al., 1994; Richardson et al., 2008; Widén et al. 2010).

The first work on bottom-up model was made by Walker and Pokoski (1985). To model domestic electricity demand, they introduced availability functions and proclivity functions. Modellers used different inputs to construct their models such as publicly available statistical data, measured appliance usage data and Time Use datasets based on diaries reporting households' daily activities. For instance, Capasso et al. (1994) employed distributions based on demographic surveys over family types and appliance ownership to generate appliance use profile. Gottwalt et al. (2011) used the corresponding statistical appliance data for Germany as input parameter to develop a bottom–up model to investigate the impact of smart appliances and variable prices on electricity bills of a household. Paatero and Lund (2006) develop a bottom-up tool to artificially generate domestic electricity consumption time series that are well correlated with empirically measured reference data. They use a simple demand side management simulation and only estimate the effects on peak load from shifting. Recently, there is a significant interest in activity-oriented electricity demand modelling where the overall electricity demand profiles are constructed by using Time Use datasets (Tanimoto et al., 2008; Robinson et al., 2011; Widén et al., 2012). The major drawback of the activity oriented approaches is that participants have to write down their daily activities each 10 or 15 minutes; therefore the switch on times cannot be identified precisely.

The dependence of the model on significant explanatory variables is crucial in order to allow for a reliable model application to predict domestic electricity demand profiles and study the demand response techniques. Therefore, it underlies the need of a validated methodology which enables to predict the distribution of domestic electricity demand profiles as a function of influencing parameters.

A similar bottom-up approach (White Box Model) to Paatero and Lund (2006) and Gottwalt et al. (2011) is taken, however the time-dependence of duration of appliance usage and different power demand for each use are considered in the model instead of attributing same constant power for and the same duration for every appliance usage.

Dataset

The modelling framework developed in this work is based on the measurements carried out at the appliance level during "The Household Electricity Use Survey (HEUS)", a large-scale national study of domestic appliance use funded by the UK Government in 2011 (DECC, 2014b). The study monitored electrical power demand of over 5,000 individual appliances in 250 homes from May 2010 to July 2011. Of the 250 households surveyed, 26 were monitored for one year period and the rest were monitored for periods of one month at intervals throughout the year. Appliances are organized in a code scheme; the result is detailed data points where the power demand of the individual appliances can be determined with a mix of 2-minute and 10-minute resolution. Knowledge about the domestic appliances such as the frequency of use, power rating, and or if the usage is dependent on time or not are obtained from this dataset. It is an up to date electricity monitoring data and individual appliances in addition to total house electricity demand were monitored which allows identification of very detailed activities. Lastly, individual appliances monitoring also provides power demand characteristics of the appliances such as cycles, stand-by power which cannot be derived from Time-Use diaries.

Model description

The model is built on four factors. The physical quantities for modelling the household electricity demand in this paper are i) probabilities of switching on of the appliances ($p_{s,j}(t)$) depending on the time of day, ii) the distributions of the duration iii) power curve of the appliance use and iv) frequency of usage of the appliance. For the simulation of a load curve of one appliance of 100 households, these four factors are modelled with probability density functions. The randomness is included in appliance electricity demand (AED) model by using stochastic process and probability distribution functions. Electricity demand profilesgenerated on a per-household-appliance basis and then are aggregated to create household demand profiles at 2-min time resolution. Electricity consumption data from the Household Electricity Use Survey (HEUS) is used to construct appliance electricity demand model. The basic model structure for generating a load profile of a single household is shown in Figure 1.

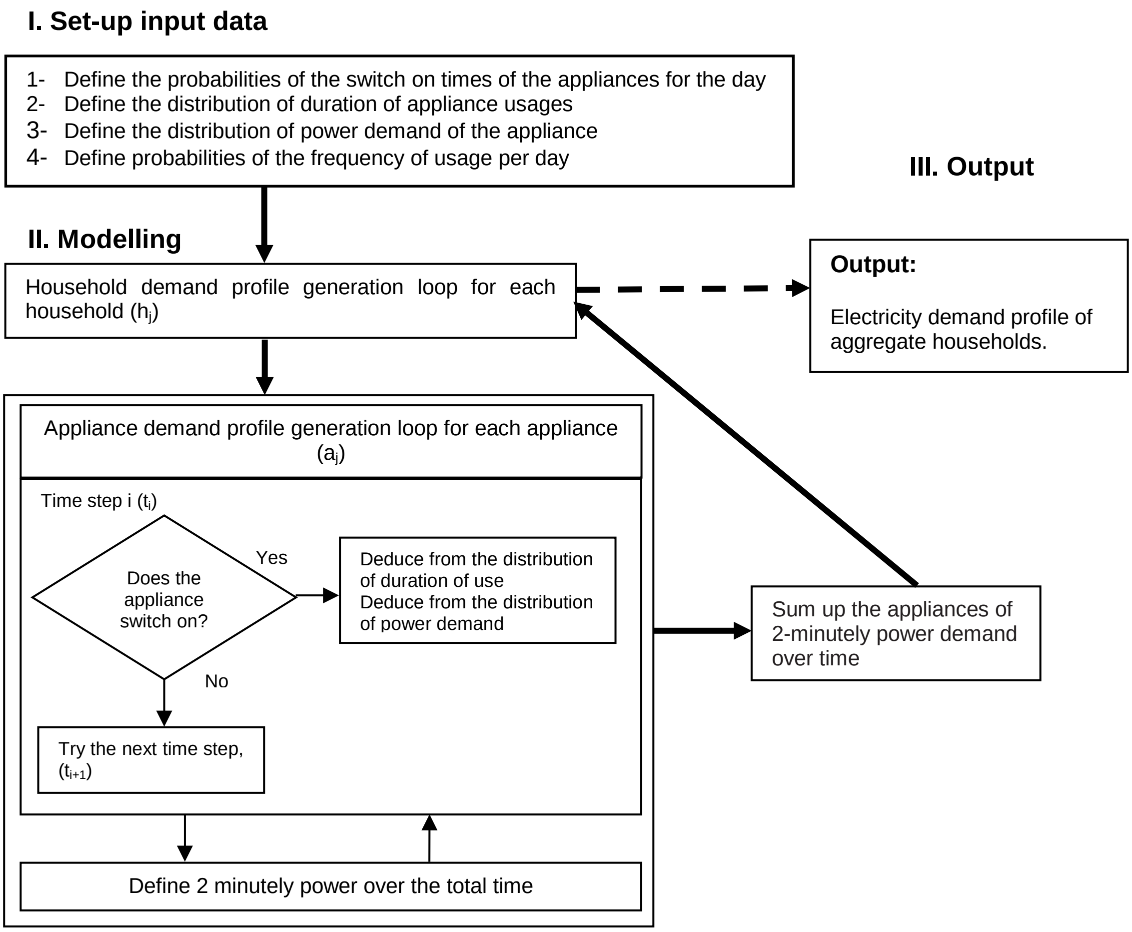

Figure 1 Diagram for the appliance electricity demand (AED) model

For simulating the switching on of an appliance, the probability of "switch on" is used for each time step of the day, i.e. to each time step (of a weekday or weekend day) is associated a value between 0 and 1 corresponding to the probability of switching that appliance on at that time of day. A modelling approach has been formulated where the switching on of each domestic appliance is tested

against 2 minutely-adjusted probabilities. The event occurs in time according to a Poisson process with parameter λ, derived from the empirical data. If the appliance is switched on, next test is done only after completion of the usage of this appliance, otherwise on each 2 minute time step. If the appliance is switched on the duration of its use and the power at which the appliance is used simultaneously are deduced from the corresponding distribution entered as an input.
The Poisson distribution is used to simulate the duration of use of appliances and power demand. For some appliances the duration of the usage is dependent on the time of the day. This property can be observed by TV and ICT. For other appliances, such as the washing machines, dishwasher or kettles, time of the day is not taken into consideration therefore the durations are deduced from the whole distribution. When deducing the power demand for the appliances such as the washing machines, dishwasher or kettles; different power consumptions can be assigned for every use by the household. For example, washing machines power consumption could depend on the quantity of clothes, the water temperature and the programme length determined by the household or for kettle, the amount of wattle filled though it is the same kettle. Therefore, power demand will be simulated for each usage. For other appliances such TV or modems, the power demand deduced will be the same for every usage for the particular household.
The established model is then applied to demand shifting of washing machines with automated response to evaluate the extent that electricity demand could be shaped by time shifting. The probability selecting the smart start option for appliances are changed for the determined times. As it is the probabilities that change, the chance of an action (action of a household demand shifting) is increased or decreased. This approach gives a diverse demand response which again ensures a realistic stochastic behaviour of the model. The model is implemented as a MATLAB script.

Results

Data Analysis to define the probability density functions

Only monthly monitored households are analysed due to high resolution of appliance monitoring (2-minutes). Another reason for choosing the monthly monitored households for data analysis is to keep the number of days observed equal from each household. However, the monthly monitored households were monitored for different periods throughout the year. The analysis shows that from this dataset, the seasonality cannot be shown since it is not understood whether the variance in daily mean appliance usages in months are due to different households or different months. The income or the household types were not discussed in this paper.

Switch-on Probabilities

The switch-on time represents the beginning of the use of an appliance (TV) or the beginning of the cycle of an appliance (washing machine). For each time step, the start time probability would be the sum of measured "switches on" events observed divided by the total number of time steps of days. Each time step of a day is associated a value between 0 and 1 corresponding to the probability of switching that appliance on at that time of day. Probability at time step (i) is calculated as such:

$$p = \frac{number\ of\ events\ that\ the\ appliance\ was\ switched\ on}{number\ of\ observations * total\ time\ steps\ of\ the\ day}$$

The probabilities of the switch-on times of washing machines on weekends and TVs on weekdays are shown in Figure 2 and Figure 3.

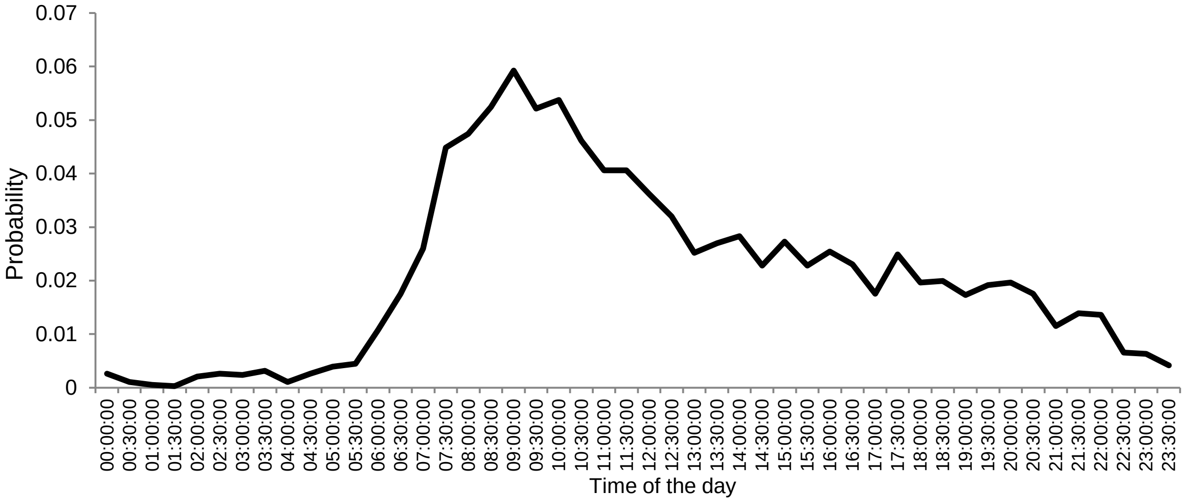

Figure 2 Daily probability profile of switch-on times of washing machines for weekend (based on monitored households; n=184 household, 3826 observed washing machine usages)

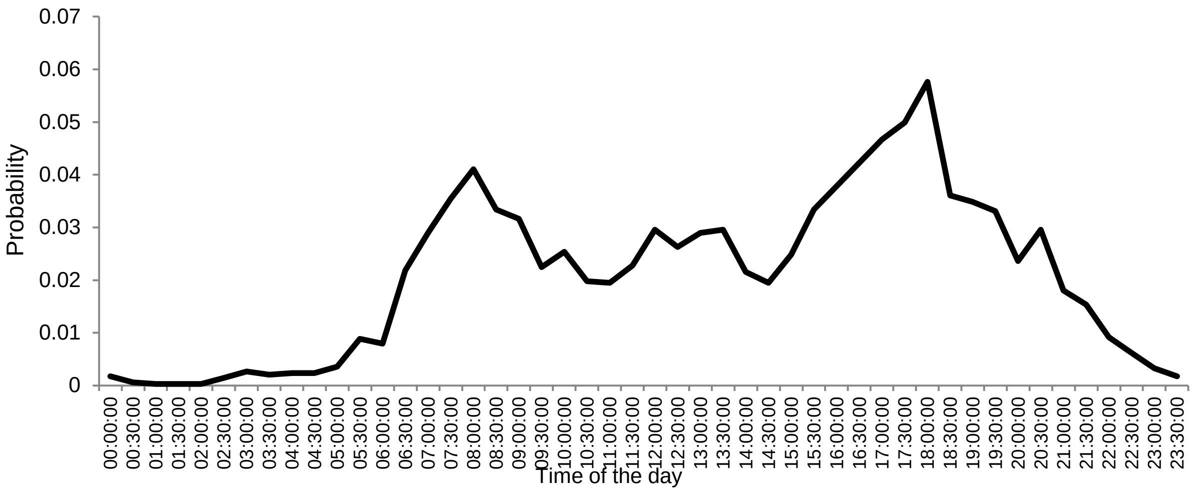

Figure 3 Daily probability profile of switch-on times of TVs for weekend (based on monitored households n=225 household, 12738 observed TV usages)

Highest probabilities of switching on the washing machine and TVs were calculated in the morning around 09:00 and in evening 18:00, respectively. The probability of switching on the washing machines and TVs at late night (12:00am to 04:00 am) was quite low compared to the other times of the day.

Duration of the appliance usage/cycle

From the data set, it was observed that the duration varies depending on the appliances and times of the day. Figure 4 and Figure 5 show the minimum, maximum and the mean values of the duration of the washing machine and TV usage started for the indicated hourly time slot, respectively.

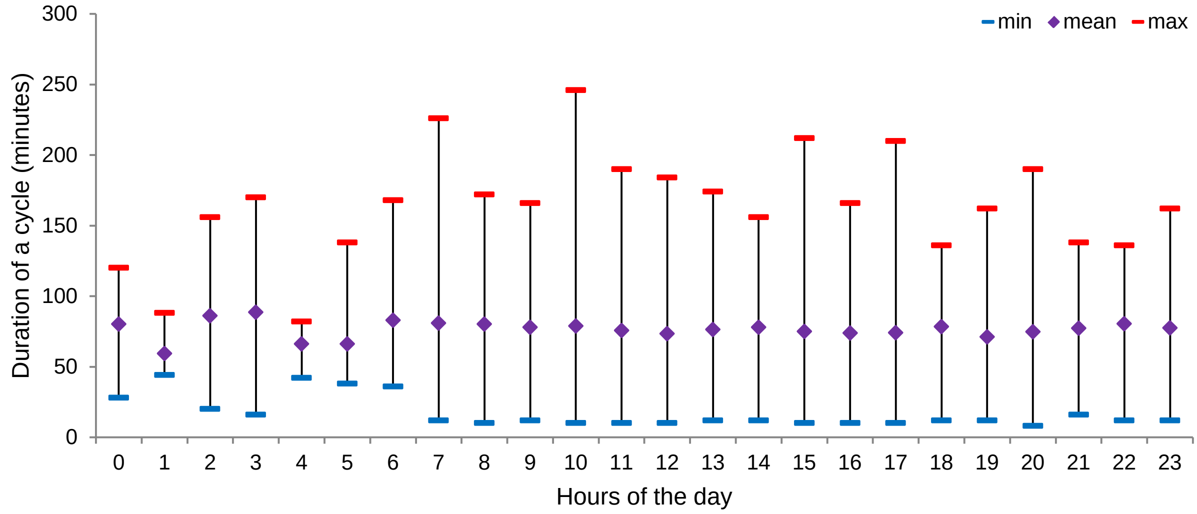

Figure 4 Durations of washing machine cycles (minimum, mean and maximum values) that are started in the time interval (on the x-axis) (n=184 households, 3826 observed washing machine cycles)

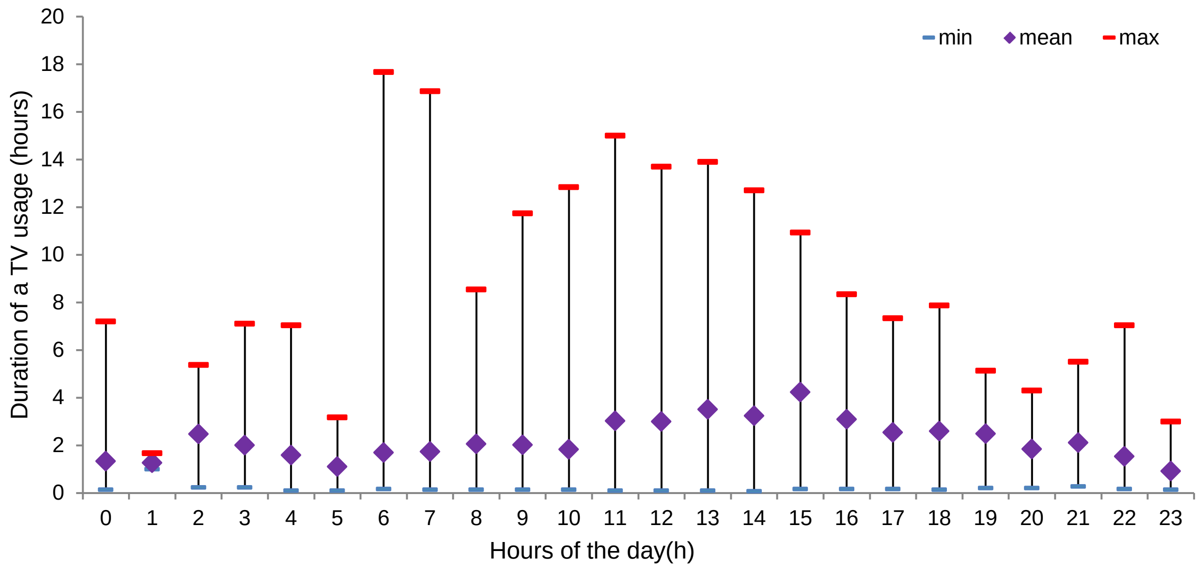

Figure 5 Durations of TV usages (minimum, mean and maximum values) that are started in the time interval (on the x-axis) (n=225 household, 12,738 observed TV usage)

The duration of the washing machines did not differ significantly depending on the time it is started whereas the duration of TV usage strongly depends on the times of the day it is started. The mean value of the duration of the washing machine for each hourly time slot changed between 59 to 89 minutes. On the other hand, duration of TV usage is observed to be shorter if it started in the late night (12am to 2 am), whereas the duration is longer when the TV is switched on in the late afternoons (2pm to 4pm). The mean value of the duration of the TV usage for each hourly time slot changed between 3 to 4 hours, highest at 3 pm. Therefore in the model, the distribution of duration is separated for each hour and the values are deduced from the distribution of the corresponding time slot for TV.

Power demand of the appliances

The average power demand of the appliance for each cycle/usage is also analysed. Figure 6 and Figure 7 show the boxplots of the average power demand of each usage of washing machines and TVs. The range of average power is quite high for washing machines whereas it is low for TVs. It is because households might have used different programmes for the washing machines for every usage whereas for TV power demand is the same for every usage though the duration could be different. Therefore in the model, while simulating the power demand of TVs, one power demand is deduced for the first usage and this power demand will be the same for the coming usages. However, for washing machine, power demand will be simulated for each usage.

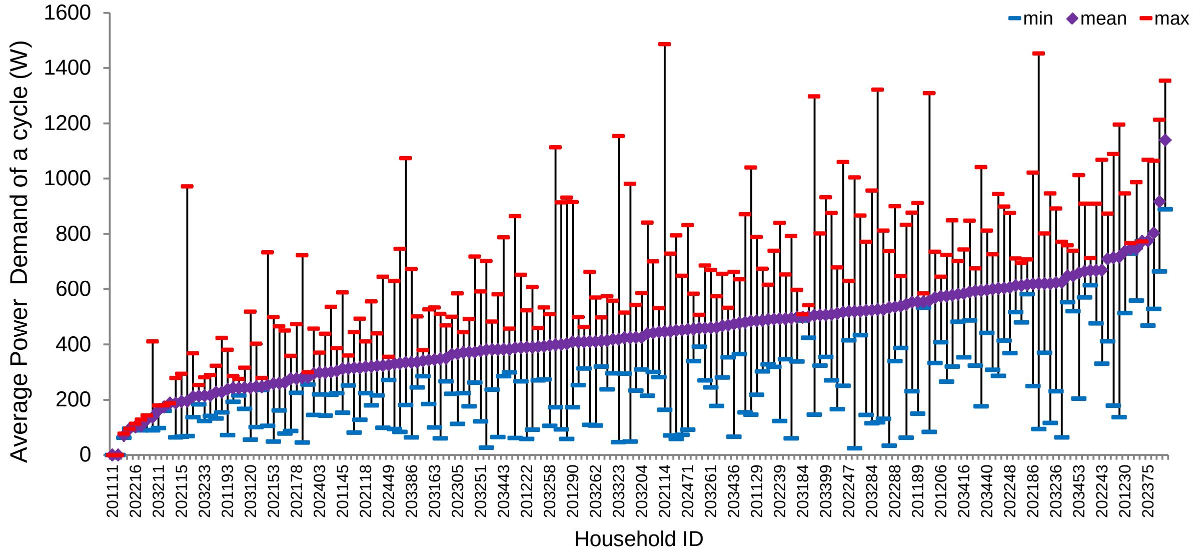

Figure 6 Average power demand of the washing machine cycles for each households (n=184 households, 3826 observed washing machine cycles)

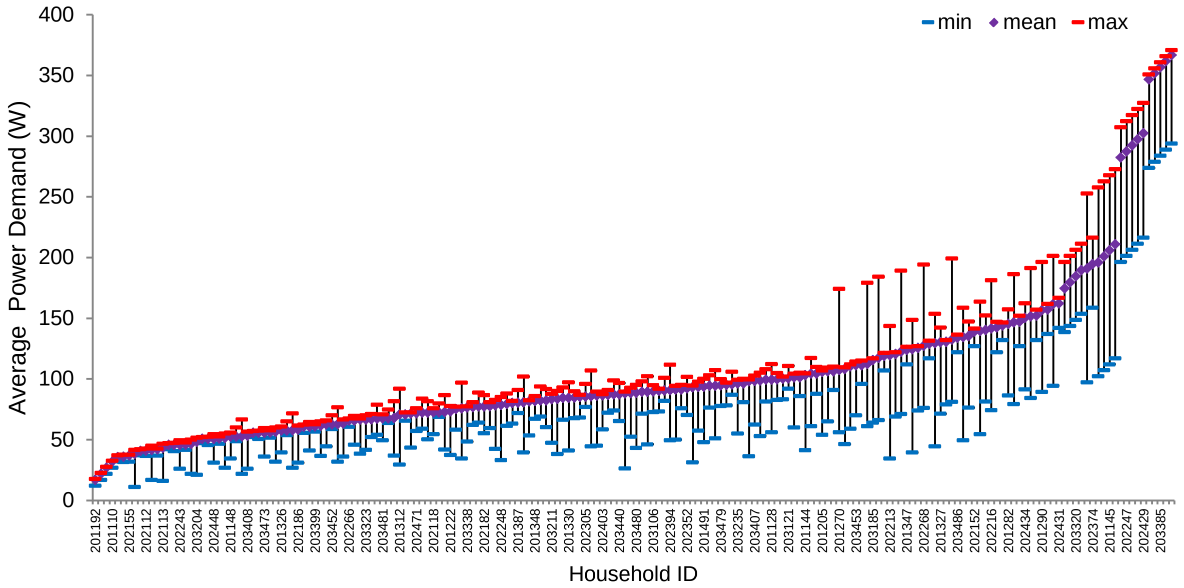

Figure 7 Average power demand of the TV usage for each households (n=225 households, 12,738 observed TV usage)

Frequency of usage of appliances

The mean daily starting frequencies for each appliance are defined (Table 1). The TVs can be switched on a day, or washing machine may not be used for a particular day. The frequency of usage is an important factor defining the switch on events therefore, for washing machines simulations are separated for as Monday, other days (Tuesday, Wednesday, Thursday and Friday) and weekends, whereas for TV, it is only weekdays and the weekends.

Table 1 Analysis of washing machine and TV usage for monthly monitored houses

	Mean daily frequency of usage (cycles/day)	
	Washing machine	TV
Monday	0.8	1.9
Tuesday	0.7	1.9
Wednesday	0.7	1.9
Thursday	0.7	2.0
Friday	0.7	2.0
Saturday	0.9	1.8
Sunday	0.8	1.8

AED model results

Using the AED model described above, electricity demand profiles of 100 households with washing machines have been generated for continuous 28 days applying the procedure in Figure 1. The simulation results have been generated by taking the average values of 100 simulation runs. The probabilities of switching of the washing machine of simulated and measured washing machines usage are compared in Figure 8. The probability of switch on are more or less evenly scattered over the time steps of an average day.

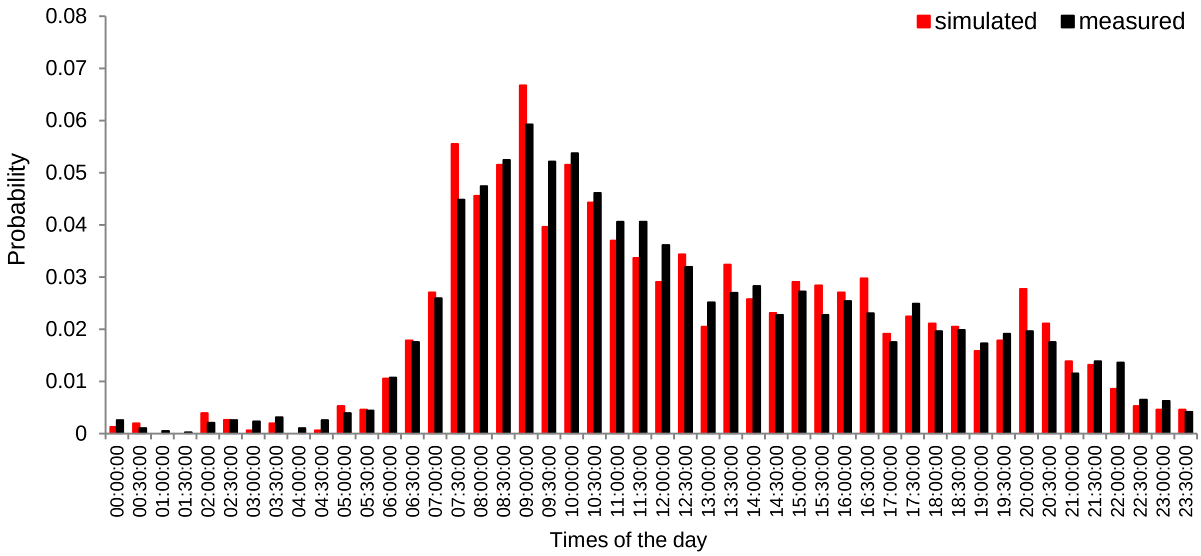

Figure 8 Half hourly (30 minutes) probability of switching on a washing machine of a day (in black the measured profile entered, in red the profile resulting from 100 simulations for 28 days)

Figure 9 shows that the peak demand values were estimated reasonably; however the model underestimated the power demand in the morning although the switch on probability was estimated well shown in Figure 8. The reason for the mismatch in the morning peak power could be due to the power distribution of the washing machine. For instance, seasonality was not considered for the washing machine data therefore, the power demand of the washing machine due to amount of clothes changed during different seasons might not been integrated well in the model. However, the difference was 9 Watts the most.

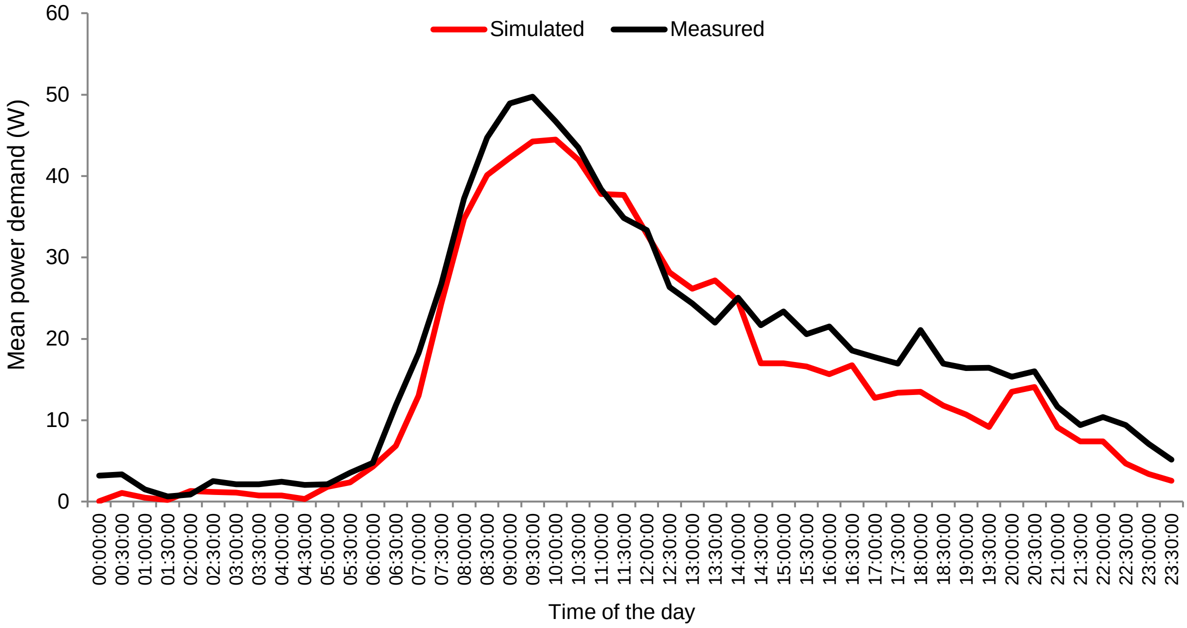

Figure 9 Comparison of the mean half hourly power demand of the washing machines for 184 households and 100 simulated households versus times of the day (Mean power demand for each half hour is calculated by dividing the sum of power demand by the count the number of records of that time in the dataset)

Of the properties used to test the model the daily frequency (i.e. average number of times the appliance is switched ON per day) does reasonably well. The mean of the monthly frequency of usage of generated 100 households was 19.25, close to monthly mean of frequency of usage by the monitored houses (19.6 times per month). Daily frequencies are shown in Table 2.

Table 2 Comparison of the monthly frequencies of the washing machine usage for measured and simulated households

	Mean daily frequency of usage (cycles/day)	
	Measured	Simulated
Monday	0.8	0.71
Other weekdays (Tuesday, Wednesday, Thursday, Friday)	0.7	0.62
Weekend	0.8	0.80

Demand shifting

The demand shifting is explained using a washing machine as an example. Demand shifting is modelled by defining a new probability for switching on the washing machine for a particular time slot. In this example, cheapest slot is determined as 9 pm. 9pm is chosen randomly in this study. However, a time slot can be determined according to several surveys stating which time slots people are willing to shift their appliance usage or this time value can be determined according to time based electricity tariffs choosing the cheapest slot. The probabilities of selecting a new switch on option for washing machines that is starting at 9 pm are shown in Table 3. The new probability of the washing machine starting at 9 pm is determined as 20%, 40% and 60% for Scenario 2, Scenario 3 and Scenario 4 respectively. These values do not depend on any empirical data and they only show the probability of switching on the washing machine at 9 pm.

Table 3 Parameter of the simulated scenarios:

Scenario	Switch-on probability for 9 pm (%)
1	No change
2	20
3	40
4	60

The model was run for only 9 pm with the new probabilities defined. For instance, if the switch on occurs at 9 pm with newly defined probability, it means the washing machine is shifted. If not, the washing machine is switched on as in the un-shifted scenario (Scenario 1). If the household didn't use any washing machine in the un-shifted scenario, the model was not run for that day with the new probability data to ensure shifting only occurs when there is a usage in the day.

Figure 10 compares the power demand profile of the washing machines of households shifting the start of their washing machine at 9 pm (Scenario 3) with the un-shifted scenario (Scenario 1). Flat tariff is shown is where there was no demand shifting of the washing machine. Values shown are the average for all 100 households simulated for the scenarios.

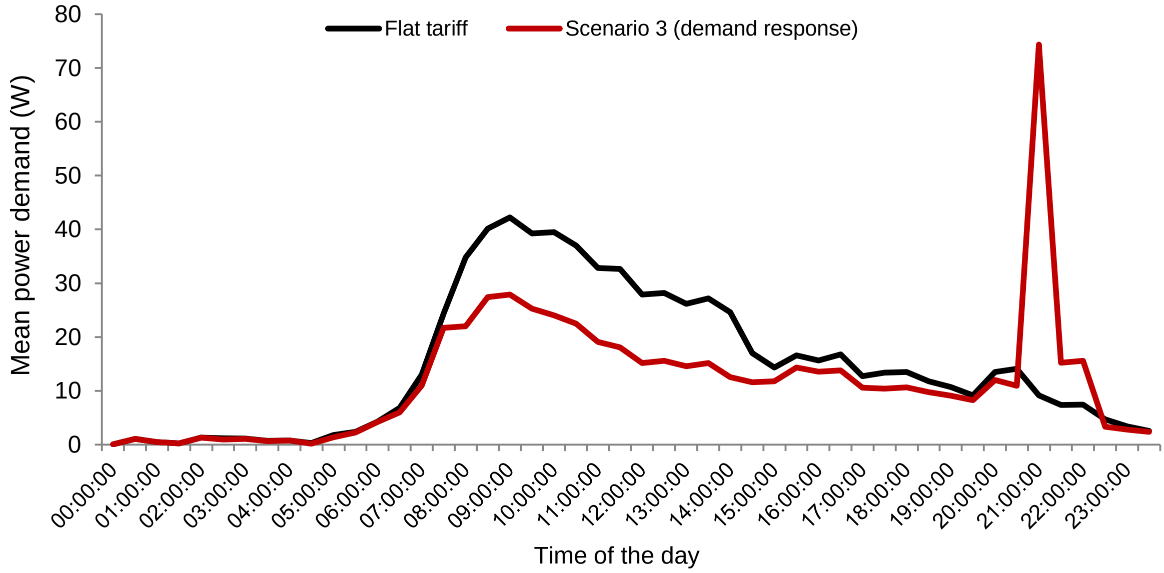

Figure 10 Comparison of average power of washing machine for the flat tariff scheme (Scenario 1) and households shifting the washing machine for the cheapest time slot, 9 pm. (Scenario 3). (n=100 households).

Figure 11 shows the net changes in power demand per half hour for Scenario 3 from flat tariff (Scenario 1) for 100 households. New peak demand is observed for 9 pm, however, there is flexible power demand with the shifting of washing machines. There was a decrease in the morning peak.

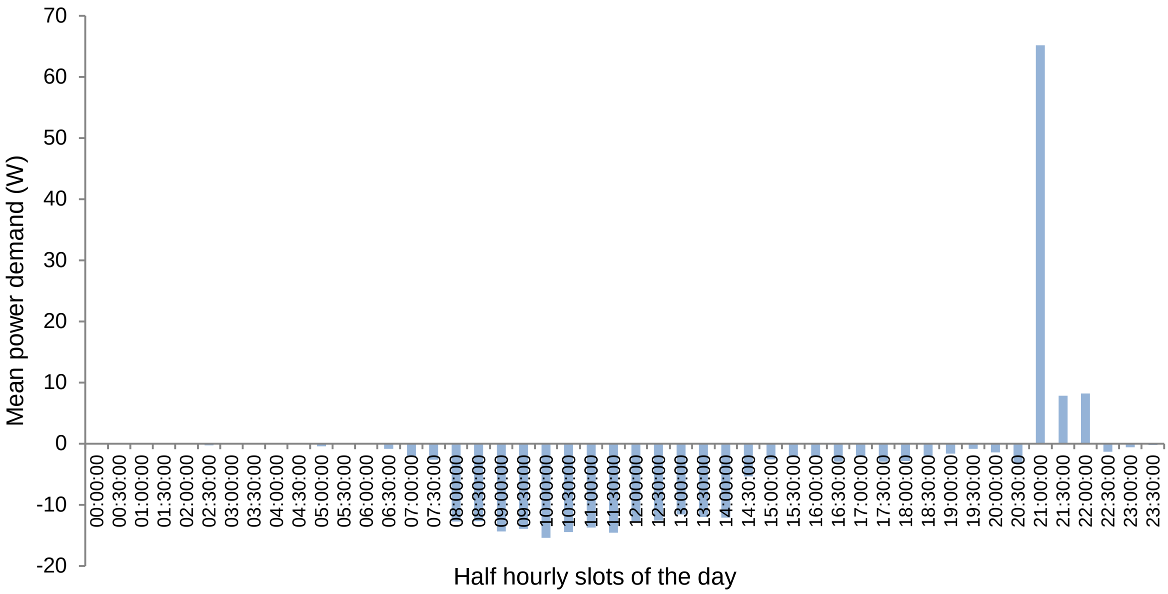

Figure 11 Half Hourly net power demand changes explaining the differences in the load curves between flat tariff and Scenario 3.

When modelling the demand shifting stochastically, as it is the probabilities that change, the chance of action that the washing machine is switched on for the cheap time or the expensive time slot according to the price signals is increased or decreased. Since not every household would respond to the price signals, only some portion of that might respond and it has to be determined stochastically. This approach gives a diverse demand response which again ensures a realistic stochastic behaviour of the model. This could model can also be applied to investigate the impact of other appliances such as dishwashers, water heaters and dynamic price tariffs (time of use) on electricity bills of a household.

Conclusion

This paper describes the development of a modelling framework to quantify the demand response potential. The analysis of washing machines and TVs in terms of switch-on times, duration, power curve and frequency of usage are presented as examples to identify the appliance usage patterns and electricity use by the households for developing the model. The analysis shows:

- The probability of appliance switch-on events depends on the time of the day.
- The duration of the washing machines does not differ greatly depending on the time it is started whereas the duration of TV usage strongly depend on the times of the day it is started.
- The power consumption of washing machine cycles could be different each time it is used; however there is much less difference in the power demand of TV each time it is used.
- The switch on times of the appliance and the frequency of the usage depend on the days of the week.

The modelling framework demonstrates accounts for all of observations above. A simple demand shifting case is shown for washing machines. The stochastic demand shifting simulation makes the shifting of washing machines to the cheapest time slot at 9 pm. Washing machine enables the hourly power demand flexible, but creates new alternative demand peak values. The mean power demand for an average house is reduced between 1 W to 15 W from the morning hours slots (measured morning peak value = 50 W).

The income or the household types were not discussed in this paper. However clustering the households depending on the occupancy number or household type could significantly increase the accuracy of the model as the energy patterns differ among the household types. The authors are also analyzing the yearly measurements of appliance electricity consumption of 26 homes at 10-min intervals to integrate the seasonality factor. Future work will allow demand shifting of many other appliances for different tariffs such as defining shifting probabilities for several time slots rather than one or putting limitations for the time where the appliance can be shifted.

Acknowledgements

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Nomenclature

AED = Appliance electricity demand

HEUS = Household Electricity Use Survey

p= Switch on probability

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Demand Response and Energy Storage for Zero Energy Residential Buildings

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Abstract

The EU climate and energy targets and the decreasing costs have been leading to a growing utilization of solar photovoltaic generation in residential buildings. However, even in buildings with the same level of yearly generation and consumption the mismatch between the demand and the photovoltaic generation profiles leads to high power flows between the household and the grid, which is an inefficient mode of operation. Therefore, new solutions are needed to increase the matching between the demand and the available generation.

This paper presents a novel energy monitoring and control system which integrates a PV generation and storage system designed for the residential context. Such system increases the matching between the local generation and consumption using lithium-ion batteries as storage device and the rescheduling of washing and drying appliances and the control of thermal loads (e.g., refrigerators or HVAC) as demand response resources. The system is controlled with the objective to minimize the power flows between the household and the grid, as well as to reduce the costs of operation.

1. Introduction

The household of the future should progressively become a Nearly Zero Energy Building (nZEB), and, to achieve it, the use of self-generation is fundamental. In residential buildings, photovoltaic (PV) generation is the most adopted technology and presents a fast-growing penetration [1]. However, unlike conventional capacity, PV generation cannot be reliably dispatched and exhibits significant temporal variability. Additionally, in residential buildings, the PV generation and electricity consumption do not have the same variation profile and such mismatch brings the need to export to the grid a significant part of the locally generated energy, even though the same amount of energy is later imported back for local consumption. These aspects are a source of inefficiency and create problems on the electrical grid management and can be even a source of economic losses to the end-user (in situations where the price paid by the consumed energy is higher than the price received by the energy injected into the grid).

At the same time, the energy consumption in European Union (EU) households has been steadily growing during the last few years due to the widespread utilization of new types of loads and the requirement of higher levels of comfort and services [2]. However, if properly controlled, several residential appliances can be used as a Demand Response (DR) resource, therefore contributing to minimize the mismatch between the generation and consumption [3]. Washing and drying appliances can be rescheduled to periods of lower energy consumption (thus flattening the demand curve) or of higher energy generation coming from renewable sources (thus matching consumption with renewable generation). The thermal loads (cold appliances, water heating or space conditioning) can be interrupted during shorts periods of time, without major reductions of service quality, to avoid the most unbalanced situations between generation and consumption, compensating the effects of the variability and randomness of the renewable resources availability.

Meanwhile, energy storage has emerged as a very important solution for this new paradigm, since it can store the surplus of generation to be used later in the periods with high consumption and small or null generation [4]. The cost of the storage technologies is decreasing, and soon it is expected to become economically suitable for small applications.

At the same time, new real-time monitoring and control systems have been developed to the residential sector to achieve energy and costs savings. Such systems could also be used to ensure optimization objectives and to improve the grid reliability, using electrical appliances as a demand response (DR) resource and managing the energy storage resources. This paper presents a novel energy monitoring and control system, based on the architecture developed by the ENERsip project [5] (other projects such as the Power Matching City project also use a similar architecture [6]), which integrates a PV generation and storage system designed for the residential context. Such system ensures the matching between the local generation and consumption using lithium-ion batteries as storage device and the rescheduling of washing and drying appliances and the control of thermal loads (e.g., refrigerators or space conditioning) as demand response resources.

The remainder of the paper is structured as follows. Section 2 presents the sizing of the PV and storage systems with the aim to convert a residential building in Portugal into a nZEB. Then, Section III, presents the design of the generation and storage system, as well as the information and communications technology (ICT) architecture that enables its monitoring and control. Section 4 presents the energy services offered by the system and its role on the optimization tasks. Section 5 presents the assessment of the impact of the use of DR and energy storage from the technical and economic point of views. Finally, Section 6 summarizes the paper, emphasizing its main conclusions.

2. Sizing of the System

In order to achieve a Zero Energy Building, the architecture and thermal optimizations are not enough, but also improvements in the electrical systems are needed. Furthermore, it is important to know how much renewable energy and storage capacity are needed and how they should be managed to optimize the expected benefits for the grid and for the customer. Therefore, a PV and energy storage system was sized to the average Portuguese household.

The survey on energy consumption in the residential sector, developed by the National Institute of Statistics and the Direction-General for Energy and Geology [7], assessed the average consumption of electricity per household in Portugal as 3673 kWh/year, which is about 10 kWh/day. Such survey also assessed the ownership rates of each type of appliance in the Portuguese households. Then, the electricity consumption breakdown in EU households was used as reference [2] and adapted to the Portuguese reality using the ownership rates of each appliance. Figure 1 presents the load profile considered for an average household in Portugal.

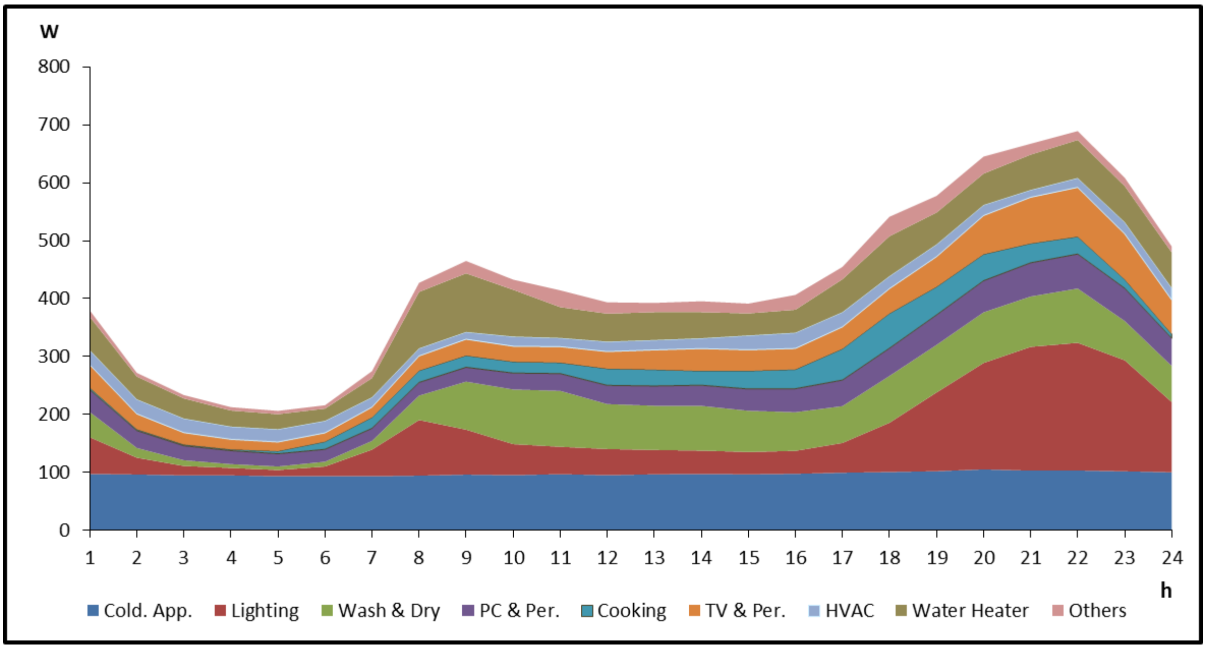

Figure 1: Load profile of an average household in Portugal

Considering the average solar radiation conditions in Portugal, the generation system was sized in order to ensure an average generation level equivalent to the average energy consumption (3673 kWh/year). To ensure such conditions a PV system with a total of 2.4 kWp is needed. Therefore, it was considered the use of 10 PV panels with 240 Wp, connected in 2 strings of 5 panels in series.

It was preciously assessed that to ensure a good level of generation and consumption matching, an effective energy storage capacity of 60% of the average daily consumption is needed [8]. Therefore, to the average Portuguese household the needed effective capacity of the energy storage system is about 6 kWh. Additionally, to avoid a quick degradation of the batteries, the State of Charge (SoC) should not be lower than 30% (increasing the needed capacity to 8.57 kWh). Considering the use of lithium-ion batteries with an efficiency of 92%, the needed minimum storage capacity is 9.32 kWh. However, the default value available in the market is 10.2 kWh. Therefore, to achieve a nZEB level in an average residential building, the use of a PV system with 2.4 kWp and an energy storage system of lithium-ion batteries with 10.2 kWh was considered.

3. System Architecture

3.1 Generation and Storage System

Figure 2 presents the proposed configuration to the grid connected PV generation and battery storage system. The 2.4 kWp PV array is connected to the DC bus by a boost converter with the duty cycle controlled to ensure the Maximum Power Point Tracking (MPPT) using an Incremental Conductance algorithm [9]. The MPPT algorithm ensures that the PV panel provides always the maximum power, regardless the load connected to its terminals, playing an important role for this kind of solar energy utilization, since it increases the PV panel efficiency. Its implementation is done through a DC-DC converter, and the operating principle consists in regulating the converter duty cycle in order to regulate the voltage (or current) output, extracting, thereby, the maximum power from the panel.

The 10.2 kWh (200 Ah, 51.2 V) lithium-ion battery is connected to the DC bus by a bidirectional DC-DC converter. The battery charging and discharging processes is ensured by the bidirectional DC-DC converter which operates in buck mode, during the charging process, and in boost mode, during the discharging process. The duty cycle of the bidirectional DC-DC converter is controlled according to the amplitude of the needed charging or discharging current. The DC bus is connected to the grid and to the loads by a 5 kVA, 100 kHz inverter, controlled by the hysteresis current [10].

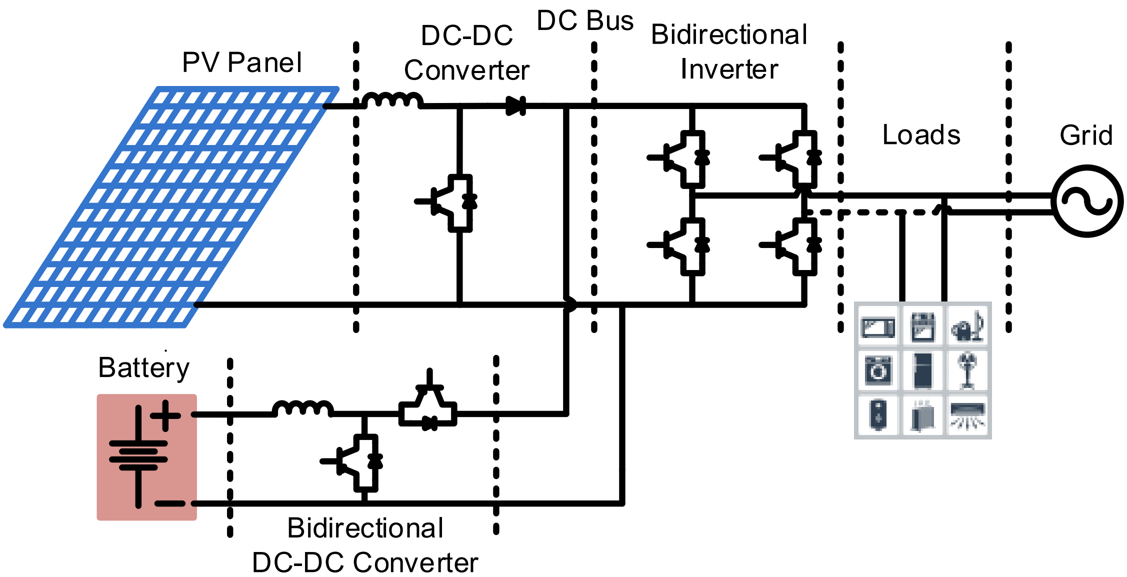

Figure 2: PV generation and storage system

3.2 Monitoring and Control Communications System

Monitoring and control communications infrastructures are crucial in order to achieve on-site consumption and generation matching in practice, since they allow collecting in almost real-time the consumption and generation data required by the optimization algorithms and delivering the appropriate commands at due time. As it has already been mentioned in section 1, the monitoring and control system for the consumption and generation infrastructures of nZEB proposed in this paper takes the communications architecture developed in the EU FP7 project ENERsip as baseline [5]. However, it has been updated to adapt it to the new specific scenario (including energy storage) and market trends.

Figure 3 shows an overview of the proposed monitoring and control communications system. As it can be seen, the sensors and actuators for the consumption and generation infrastructures communicate with the so-called Home Energy Manager (HEM). The protocol stack used for such communications is left open to implementation, being assumed that the communications requirements of the proposed optimization algorithms (e.g., in terms of latency) are met.

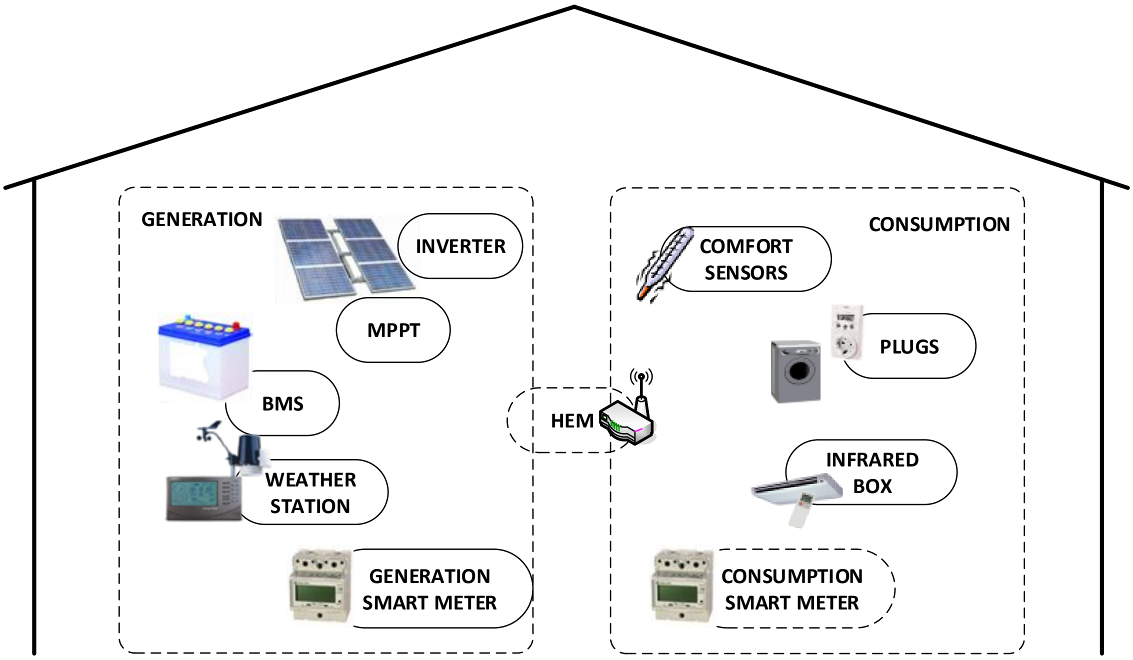

Figure 3: System architecture

The sensors and actuators considered for the consumption infrastructure are: Smart Plugs, Infrared Box, and Comfort Sensors [11]. The Smart Plugs are placed between the plugs of the appliances and the wall sockets. The Smart Plugs measure the consumption of appliances such as washing machines or driers and send it to the HEM, and also act on the power supply of such appliances by cutting it OFF or ON. The Infrared Box enables managing IR-controlled appliances, such air conditioning or multimedia devices such as TV or DVD, remotely. Both the Smart Plugs and the Infrared Box allow the integration of legacy appliances into the in-house/in-building monitoring and control system right away, thus enabling putting the proposed optimizations into practice even before the “smart appliances” come to the market. Finally, the Comfort Sensors measure different environmental variables, such as temperature, relative humidity or CO_2 concentration, which need to be taken into account by the optimization algorithms to avoid compromising the users’ comfort levels.

As it has already been explained, the equipment considered in this paper in the on-site generation infrastructure involves photovoltaic panels and lithium-ion batteries. The sensors and actuators considered for this infrastructure are: Inverter, MPPT, battery management system (BMS), and Weather Station. The Inverter is associated to the PV panels and is responsible for DC-AC conversion. The MPPT module is also associated to the PV panels and works both as a sensor (measuring the voltage and current at the PV panel terminals and sending these data to the HEM) and as an actuator (controlling the duty cycle based on the commands received from the HEM, resulting from running the incremental conductance algorithm). The BMS module is associated to the energy storage equipment and manages the battery charging and discharging process by controlling the buck/boost converter. Hence, the BMS module also works as a sensor (measuring the voltage and current at the battery terminals and sending these data to the HEM) and as an actuator (handling the signal to charge or discharge received from the HEM and the current of discharge). Finally, the Weather Station gather several sensors that measure variables related to weather conditions and send these data to the HEM to enable accurate energy generation forecast. As a matter of fact, deploying a Weather Station is not actually mandatory in order to get such data, since the HEM could download them from a weather forecast web service.

In addition, a Consumption Smart Meter and a Generation Smart Meter are required to monitor and record the consumption and generation of the house/building. Such Smart Meters communicate with the Distribution System Operator (DSO), but also with the HEM (as it is currently being imposed by regulation), that uses this information to double check the effectiveness of its management commands. The HEM works both as a communications gateway and as an energy manager. Since in principle the consumption-generation matching is performed locally, the optimization algorithms run in the HEM. If this were not possible in practice (e.g., due to hardware constraints), the optimization algorithms could be run in a cloud-computing-based backend. The HEM may also communicate with the DSO and incorporate signals coming from them to its decision-making logic.

4. Energy Services and Optimization

The presented architecture enables the implementation of several energy services, such as: monitoring, remote control, demand response, local optimization and grid management.

The monitoring service provides information in real time about the energy consumption of the whole building and individual appliances and associated costs, the generation level and generation forecast, stored energy, energy injected into the grid and associated price. Such service ensures, not only an increase of the user awareness about the energy consumption (leading to energy savings), but also the identification of the resources available for optimization (loads available to be controlled, generation level and storage level).

The remote control service enables the remote control of individual appliances. The end-users can create an initial configuration of the network of energy consuming devices, turn a selected device ON or OFF, or change its properties (e.g., the air conditioning operating temperature). The parameterization of the network is a simple operation that can be done by an average household consumer, since they just have to use an intuitive interface to select the appliances, assign an operation period or turn it ON or OFF. This service is not just important to provide to the users the capability to turn OFF the appliances which are unnecessarily turned ON to reduce the energy consumption, but also to perform similar actions automatically through DR events. With such service, it is possible to turn OFF remotely any appliances and therefore the appliances used in DR can be easily controlled by the system, without the need of any manual operation.

With the demand response service, the end-user is able to specify individual devices or groups of devices to be included in the DR program (the home owners are notified about of pricing and load control events in the previously day), and consequently, those devices are directly controlled by the system (the user can also manually override it). This ensures the minimization of costs to the end-users (by shifting loads to periods with lower tariffs), but also the adequate management of DR requests received from the utility and management of loads to local optimization.

The local optimization service ensures the matching between the local generation and energy consumption. To ensure it, the service uses the demand response service by rescheduling appliances to the periods with high energy generation or by curtailing thermal loads in situations of a quick decrease of generation. Additionally, it ensures the optimization of the energy storage ensuring that a minimum SoC of 30% is always guaranteed and considering the available capacity in the battery it assess the energy to the stored, sent to the grid or consumed from the grid, in each time slot, considering the priorities presented in Table 1.

The grid management service provides to the Distribution System Operator near real-time information about generation and consumption of electricity, as well as stored energy in a given location. Such information will be very important for the DSO to the planning and dispatching of the generation resources. However, the most important impact of this service is to ensure the required conditions to operate DR programs, namely providing data about the available loads in each neighbourhood, providing communication channels to send real-time tariffs and ensuring the ability to remotely control the appliances according with the user preferences. Using the same principle, the service could also ensure the needed conditions to the use of the stored energy to provide ancillary services to the DSO.

Table 1: Priorities of the energy storage optimization

Battery	Generation > Demand	Generation < Demand
SoC = 30%	1. Needed generation to loads 2. Remainder generation to storage	1. Available generation to loads 2. Remainder energy need received from grid
30% < SoC < 100%		1. Available generation to loads 2. Available stored energy to loads 3. Remainder energy need received from grid
SoC = 100%	1. Needed generation to loads 2. Remainder generation to grid	

5. Impact of the Optimization

The global system, its individual components (PV panels, batteries, etc.) and its management and control system were modelled in MATLAB/Simulink (Figure 4). Such model was then used to simulate the impact of the control under different conditions of operation.

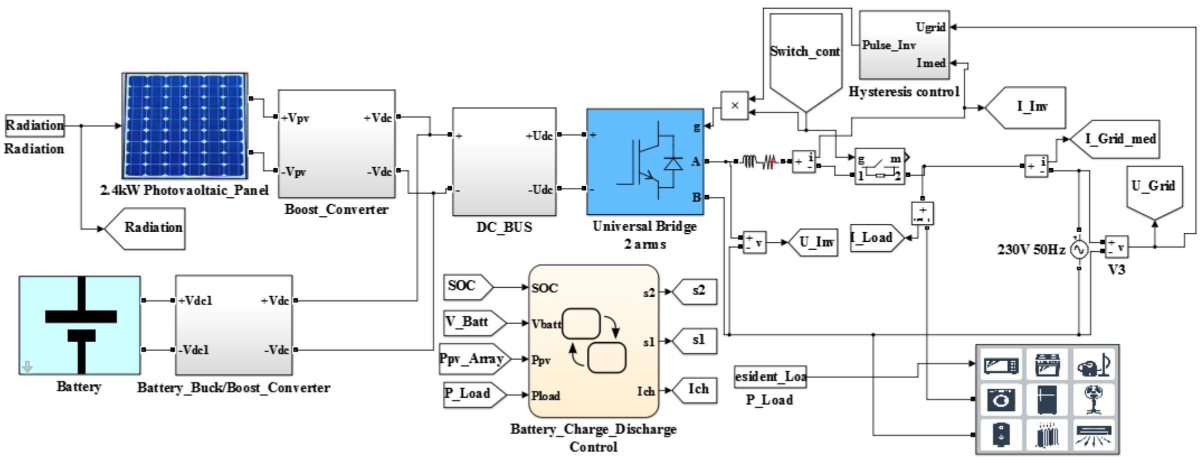

Figure 4: MATLAB/Simulink model of the system control

5.1 Baseline

The assessment was done to the entire year, but only data from three months is presented to represent different extreme conditions: August (higher generation), October (almost the same level of generation and consumption) and December (higher consumption). Figure 5 presents the generation profile, the demand profile and the exchange of energy with the grid (difference between the generation and consumption levels). In a household without control of loads and without energy storage there is a constant power flow between the grid and the household, sending most of the generation to the grid and receiving from the grid all the energy needed during the night. As can be seen in Table 2, in such conditions between 53.4% and 71.5% of the generated energy is injected into the grid (H2G) and, simultaneously, between 56.2% and 74.1% of the consumed energy must be requested to the grid (G2H).

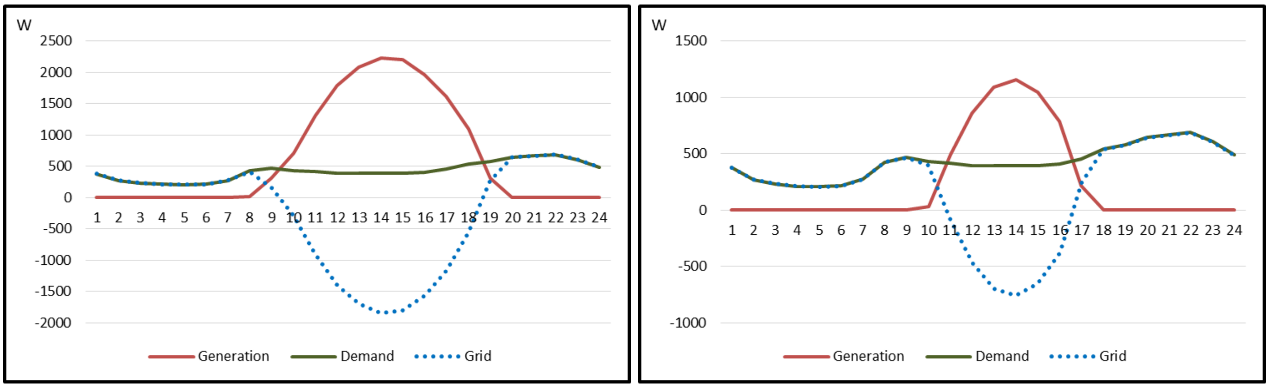

Figure 5: Generation, demand and exchange with the grid in August (left) and December (right)

Table 2: Daily energy exchange between the household and the grid

	August	October	December
H2G (Wh)	-11177.5	-6618.0	-3028.1
G2H (Wh)	5728.7	6729.0	7546.6
H2G (% Gen.)	-71.5%	-65.7%	-53.4%
G2H (% Dem.)	56.2%	66.0%	74.1%

Such high power flows do not have just a technical impact but also an important economic impact. With the new Portuguese regulation to self-consumption of locally generated electricity, the energy injected into grid is paid only with a price of 90% of the monthly average price of the Portuguese spot electricity market. During 2014 the average price of the Portuguese spot electricity market was 0.0427 €/kWh and therefore it was considered a price paid by the electricity injected into the grid of 0.0384 €/kWh. Since the energy received from the grid has a much higher cost (0.2206 €/kWh during on-peak periods and 0.1174 €/kWh during off-peak periods) any energy sent to the grid will lead to economic losses. As can be seen in Table 3, in such conditions there is an average daily cost between 0.49 and 1.21 €, since the costs of the energy consumption are much higher than the profit obtained with the energy injected into the grid (considering the same average generation and consumption).

Table 3: Energy costs

	August	October	December
Generation (€)	-0.43	-0.25	-0.12
Demand (€)	0.92	1.14	1.32
Total (€)	0.49	0.89	1.21

5.2 Demand Response

Figure 6 (left) presents the load profile from Figure 1, but aggregating the consumption by the three main types of appliances: non-controllable, interruptible and reschedule appliances. The interruptible appliances can be used for generation and consumption matching objectives by temporarily reducing or cutting the consumption of such appliances to compensate reductions in the generation. This is very important to compensate the intermittence of large scale wind power and therefore can be used to supply services to the system operator. Likewise, it can be used to the optimization between the local generation and consumption, but since it is just used in rare occasions it does not have a relevant impact on the global power flows between the household and the grid and on the associated costs. The group of appliances with the most relevant impact are the reschedule appliances, since by rescheduling such appliances to operate only during the hours with high PV generation it is possible to reduce the energy sent to the grid during the hours with generation and reduce the energy received from the grid in the hours without generation. Figure 6 (right) presents the load diagram with the considered reschedule of average consumption.

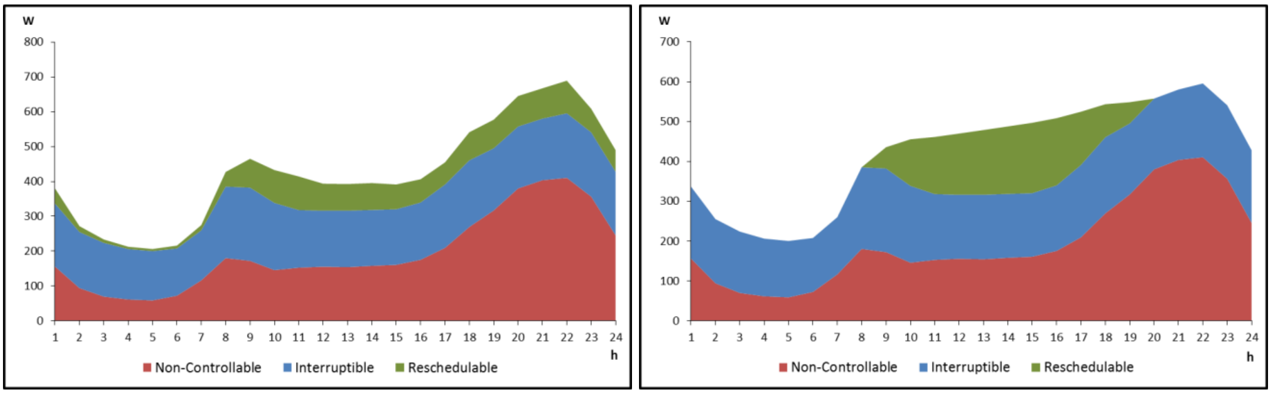

Figure 6: Load profile without (left) and with reschedule (right) of loads

Figure 7 presents the impact of the rescheduling on the energy exchange between the household and the grid. The figure presents the generation profile, the demand profile with and without rescheduling and the exchange of energy with the grid, in the scenarios with and without rescheduling. As can be seen in Table 4, such strategy leads to a decrease between 5.4% and 16.8% on the energy sent into the grid and, simultaneously, a decrease between 6.7% and 10.5% on the energy consumed from the grid

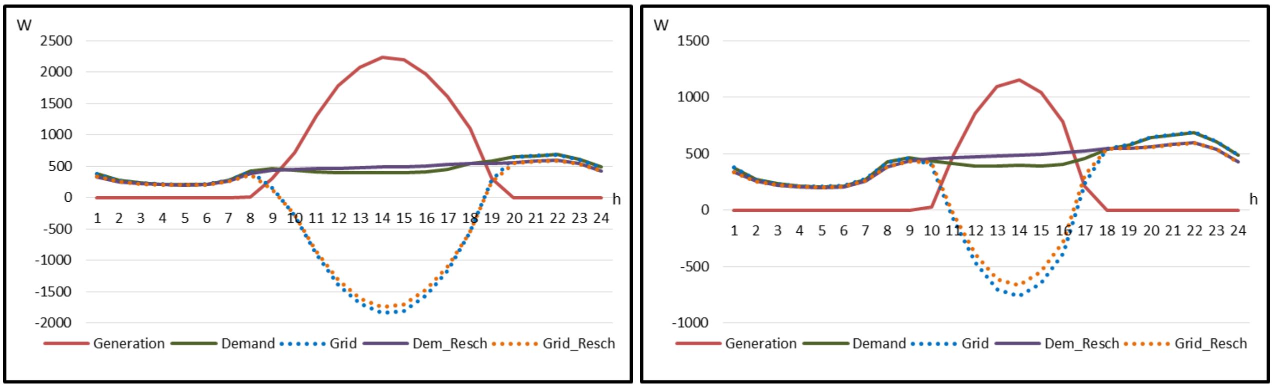

Figure 7: Generation, demand and exchange with the grid in August (left) and December (right) with and without reschedule of appliances

Table 4: Daily energy exchange between the household and the grid considering reschedule of appliances

	August	October	December
H2G (Wh)	-10573.5	-6016.3	-2519.0
G2H (Wh)	5124.7	6127.3	7037.6
H2G (% Gen.)	-67.6%	-59.7%	-44.4%
G2H (% Dem.)	50.3%	60.1%	69.1%
ΔH2G (%)	5.4%	9.1%	16.8%
ΔG2H (%)	10.5%	8.9%	6.7%

Such reduction on the energy exchanged between the household and the grid also have as impact a reduction between 5.3% and 16.5% on the daily costs, as can be seen in Table 5.

Table 5: Energy costs considering reschedule of appliances

	August	October	December
Generation (€)	-0.41	-0.23	-0.10
Demand (€)	0.82	1.04	1.24
Total (€)	0.41	0.81	1.14
ΔTotal	-16.5%	-9.1%	-5.3%

5.3 Energy Storage

By including the impact of the designed storage system it is possible to absorb the excess of energy generated during the hours with sun to use it during the night, minimizing the exchange of energy between the household and the grid. However, since there are high variations during the year in the generation, due to the limit of the storage capacity, it is not possible to entirely eliminate the exchange of energy. Figure 8 presents the variation of the SoC of the battery during an average day in August and December. As it can be seen, during August the maximum SoC (100%) is achieved (leading to the injection of energy into the grid) and in December the minimum SoC (30%) is achieved (leading to consumption of energy from the grid).

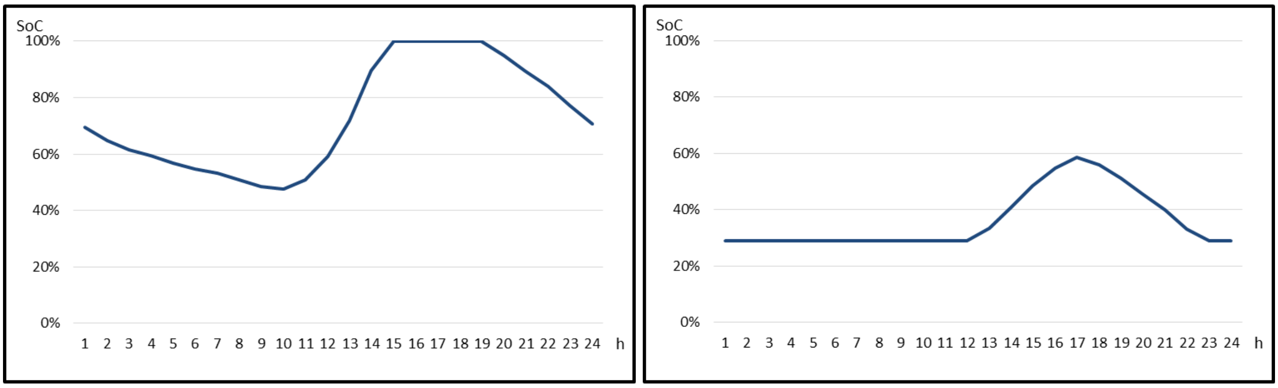

Figure 8: Battery State of Charge in August (left) and December (right)

Figure 9 presents the impact of the energy storage, showing the generation profile, the demand profile and the exchange of energy with the grid, in the scenarios with and without energy storage. With the optimization ensured by the storage system, even in these extreme situations of high and low generation, the exchange of energy between the household and the gird is low, since there is just energy sent to the grid when the SoC is 100% and energy consumed from the grid when the SoC is 30%.

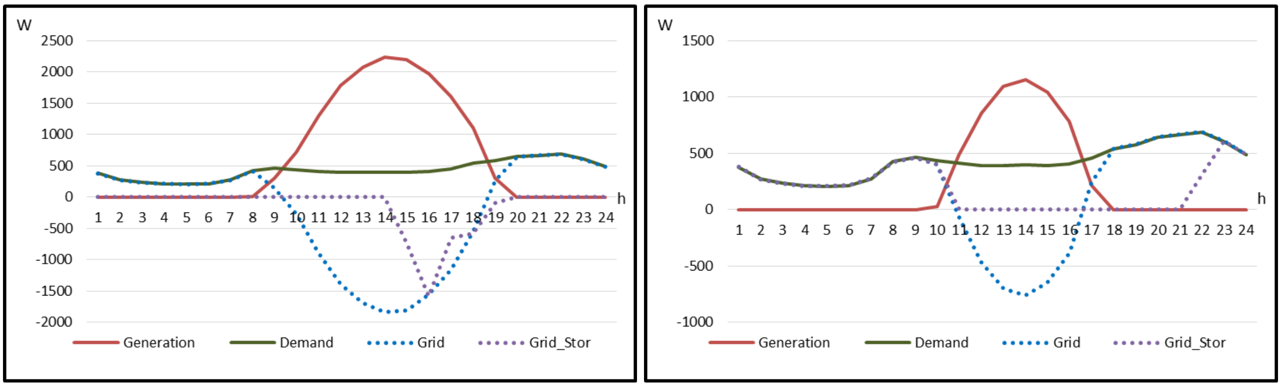

Figure 9: Generation, demand and exchange with the grid in August (left) and December (right) with and without energy storage

As can be seen in Table 6, such strategy leads to a decrease between 67.5% and 100% on the energy sent into the grid and, simultaneously, a decrease between 40.4% and 100% on the energy consumed from the grid.

Table 6: Daily energy exchange between the household and the grid considering energy storage

	August	October	December
H2G (Wh)	-3636.6	0	0
G2H (Wh)	0	123.03	4495.7
H2G (% Gen.)	-23.3%	0%	0%
G2H (% Dem.)	0%	1.2%	44.1%
ΔH2G (%)	67.5%	100%	100%
ΔG2H (%)	100%	98.2%	40.4%

Such reduction on the energy exchanged between the household and the grid also have as impact a major reduction on the average daily costs, which decreases between 46.2% and 131.8%, as can be seen in Table 7. It is important to note that the daily average cost achieved during the average month (October), and therefore the average yearly cost, is almost 0 €. This is ensured due to the reduction of the energy injected into the grid that is paid with a low price and, simultaneously, by avoiding the consumption of energy during periods of high cost.

Table 7: Energy costs considering energy storage

	August	October	December
Generation (€)	-0.14	0.00	0.00
Demand (€)	-0.02	0.01	0.65
Total (€)	-0.16	0.01	0.65
ΔTotal	-131.8%	-98.4%	-46.2%

6 Conclusions

This paper presents an energy monitoring and control system which integrates a PV generation and storage system designed to be used in residential buildings in the context of Zero-Energy Buildings (considering the same level of yearly generation and consumption). The sizing of the energy generation and storage system (using photovoltaic panels and lithium-ion batteries) was done to convert a residential building in Portugal in a nZEB. Then, the system architecture for the generation and storage system, as well as for the monitoring and control system was designed. The energy services needed for the implementation of DR actions and for the management of energy storage were defined and the optimization rules were set with the objective to simultaneously minimize the power flows between the household and the grid and the costs of operation.

The system was modelled in MATLAB/Simulink and its operation was validated showing the reliability of the designed system and its control. The model was then used to simulate the impact of the system under different conditions of solar radiation and demand. The results show that with the implementation of DR actions it is possible to achieve an average reduction of about 9% on power flows and costs. Adding the impact of the energy storage management, the reduction of power flows and costs increase to about 98%, therefore showing the key role that DR and energy storage can have in buildings with local generation.

Despite the cost savings that can already be ensured with the use of energy storage and DR in the Portuguese households with PV generation, such savings are not enough to ensure the cost-effectiveness of the system. However, due to the fast reduction of costs of energy storage devices that is projected to the next years, such systems should be cost-effective before 2020. In a future work, a prototype of the proposed architecture is going to be tested in a real household.

Acknowledgements

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Optimisation of small customer network tariffs for smart grids

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Abstract

Flexible electricity prices and electricity network tariffs can contribute to the strategic target of smart grids: increased security of supply, enforced integration of distributed renewable energy, reduced network investments, and a more efficient use of energy. Flexible prices and tariffs affect demand response by better reflecting the current capacity of the network system or currently available generation capacities. The paper analysis various types of flexible tariffs and describes their effectiveness (target-orientation). The scientific methods applied include the analysis of relevant national and international studies and more than 40 expert interviews. The institutions and persons interviewed reflect the most relevant stakeholders, i.e. the regulatory authority, distribution network operators (DNO), retailers, technology providers, domestic and corporate customer organizations, etc. Moreover, the effectiveness of tariffs was elaborated in a microeconomic approach incorporating monetary and non-monetary costs and benefits of demand response. For the case of a liberalised electricity market with a pending smart meter rollout, the paper derives optimal small customer network tariffs for the situation (i) before the rollout, (ii) after the rollout and (iii) when smart meters are rolled out and further technologies (e.g. automation at the end-user) are widespread and available.

Introduction

Integration of small-scale, decentralised, renewable and volatile electricity generation is a crucial impact factor for the development of electricity networks in upcoming decades. Before, power supply followed a more or less solely customer-influenced demand curve. Power plants could clearly be categorised to basic, medium and peak capacity plants. The mentioned changes at the supply side broke up with this clear categorisation and volatile electricity sources became the most important price determinant while conventional power plant face uncertainties and inefficiency and the transmission and distribution network (DNO) companies have to cope with enormous structural changes.

Information and communication technologies (ICT, or more common: ‘smartness’) applied in the whole supply chain can or should contribute to (partly) avoid the problems which come along with volatile and decentralised integration. The so-called *smart grid* should guarantee power quality and security of supply, enable the integration and usage of distributed generators and ideally increase energy efficiency.

One essential part of the smart grid discussion is the inclusion and utilisation of customer electricity demand. Potentials of demand response were proven to exist [1] and are thought to contribute to the above-mentioned smart grid targets. Innovative tariff models and innovative pricing models constitute the connection between the customers’ loads and the interest of electricity networks and markets. However, many barriers hinder the realisation of demand response potentials through flexible tariffs and prices. These hindrances are not exclusively of economic nature, but can also be socially, organisationally, technically or legally founded.

This paper is based the research study ‘Flex-Tarif’ [2] which was conducted for the Austrian climate and energy funds. In the study, new ‘flexible’ tariff and pricing models were analysed with regard to their effectiveness on achieving the targets discussed in the context of smart grids. The study includes technical, organisational, social, economic and legal analyses. It describes electricity pricing models and network tariff models as well as systemic problems concerning market design and split incentives between physical network operation and virtual market activity. Although some findings of ‘Flex-Tarif’ are country-specific, many results remain generalizable for industrialised countries with liberalised electricity markets. In the paper in hand, the results and recommendations derived in regard to optimal network tariff models for small customers (primarily households) are described.

Definitions

Demand response

In literature demand response is often associated with clipping peak loads or moving them to load valleys. The paper in hand includes intentional load increases (even at times of current peak loads if necessary and possible). In this paper demand response is defined according to [3]: '*Demand Response includes all intentional modifications to the electric consumption patterns of end-use customers that are intended to modify the timing or quantity, including both the level of instantaneous demand (capacity) and total consumption (in kWh or MWh) of customers demand on the power system*.'

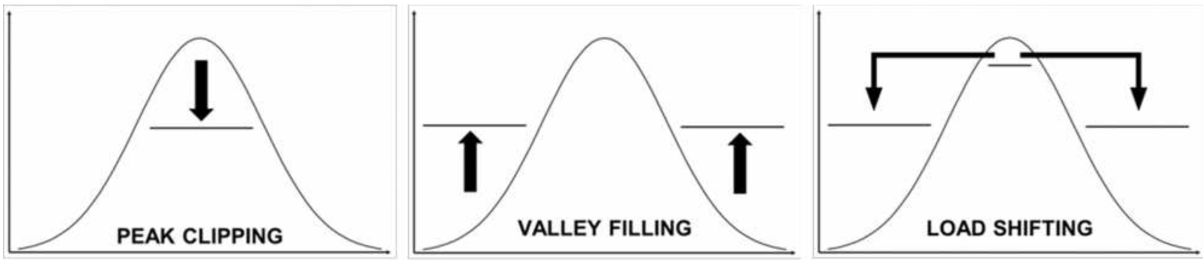

Figure 1: Classic strategies of demand response. Source: based on [4]

Strategic targets

Flexible tariffs or prices express the intention of DNO or retailers, respectively, to shift final customer's loads. Demand response (i.e. shifting loads) is assumed to be the only intention of flexible tariffs. Other parties like market facilitators (e.g. aggregators) are neglected. Other intentions of flexible tariffs like customer relationships or marketing purposes etc. are neglected.

However, the realisation of demand response is not an end in itself. Demand response aims at achieving strategic targets. The ongoing smart grid discussion is driven by the emergence of decentralised volatile generation. In the context of this discussion, the following superior strategic targets were defined:

- Use of PV and wind power: usage of the power which is generated in a volatile and decentralised manner.
- Power quality: maintenance or increase of security of supply in the short run
- Avoidance of electricity network extensions: Maintenance or increase of security of supply in the long run
- Energy efficiency: decrease of customer's electricity (energy) consumption

Tariffs versus prices

The aggregate costs customers pay for the consumption of electricity consist of a network component and an energy component. Aside of these, taxes, levies and/or fees accrue. In the following, the network component is denominated as 'tariff'. Tariffs are regulated by the responsible authority and are not subject to competition. The energy component is denominated as 'pricing model'. Pricing models are not regulated and are subject to competition.

Benchmark tariff

Based on the usual procedures with Ferraris meters a benchmark network tariff for small customers is defined as a regular fixed payment and a fixed charge per kWh consumed. (Analogously, a conventional pricing model is defined as an annual or monthly fixed payment and a fixed price per kWh consumed.) The tariffs investigated in comparison to the benchmark are all denominated as 'flexible' although some are not dynamic, variable or interruptible at all. Thus 'flexible' here denominates all non-benchmark, non-conventional models.

Flexible tariff

The authors of [5] describe various types of flexible tariffs. Additionally, non-conventional tariff models proposed by interest groups or researchers [6] were added. Previous research results [7] suggested that certain types of tariff or pricing models need to be subclassified as different results are expected (e.g. concerning the period of notice).

Alterations of the benchmark tariff

- Fixed tariff: regular fixed payment without kWh-dependency of network charges
- Load tariff: tariffs exclusively depending on maximum loads (kW)
- Consumption tariff: tariffs exclusively depending on consumption
- Contingent tariffs: tariffs with free kWh contingents or progressive consumption costs

Customer-led demand response

- Time-of-use tariff: static time-of-use-dependent kWh costs
- Real time tariffs: kWh tariffs depending on current network conditions, announced continuously
- Day ahead real time pricing: kWh tariffs depending on expected network conditions, regularly announced day ahead
- Event tariffs: kWh tariffs depending on expected network conditions, irregularly announced day-ahead

Suppler-led demand response

- Curtailable tariff: DNO can remotely curtail customer’s electricity connection to predefined kW
- Interruptable tariff: DNO can remotely interrupt electricity connection
- Remote Load Control: DNO can remotely switch on or off devices

Methods

This paper is based the research study ‘Flex-Tarif’ [2] which was conducted for the Austrian climate and energy funds. Although some findings are country-specific, many results remain generalizable for industrialised countries with liberalised electricity markets. Within the tender procedure, the Austrian climate and energy funds defined the major research questions and methods. One methodological mission was to identify all relevant stakeholders and include them in finding the results.

Expert interviews

The primary aim of the research conducted was to identify the economic, organisational, juridical and social hindrances for realising existing technical demand response potentials. These hindrances are hardly quantifiable and, moreover, according markets or technologies do not exist or are too recently introduced. Talking about a future topic, external validity (accordance of actual and intended object of investigation) cannot be guaranteed at all. Expert interviews as a scientific method probably offer the highest internal validity as experts need to explain their opinions and argumentation allows for detecting causality. Due to the non-quantitative design, one argument of one stakeholder is equally valued as one contradicting arguments stated by many other stakeholders.

Semi-structured interviews were carried out in order to ensure comparability of statements. In order to hear all stakeholders, 49 people were interviewed in 41 interviews between March and June 2014. Institutions include the majority of relevant Austrian DNOs, several departments of the energy regulation authority, electricity retailers, electricity traders, suppliers of smart meter technology, home automation systems and industry automation, PV and battery installers, customer organisations, interest groups, politicians and policy makers. In total five people were interviewed in Finland, Italy, the Netherlands and the UK. Expert interviews have been interpreted and results were joined with literature research and microeconomic analysis. In order to increase the robustness, results and recommendations were externally cross-checked with results of the German E-Energy smart grids program. Finally, results and recommendations were presented in a workshop to all the experts interviewed in order to allow for feedback and discussion (in similarity to the style of the Delphi method).

Microeconomic analysis

Different tariffs result in different incentives. Microeconomics is more than monetary benefits and costs. Thus, these incentives include non-monetary benefits and costs which have to be considered in the analysis. The microeconomic analysis aims at evaluating the effectiveness, i.e. the target-orientation of the various network tariff models.

Prices set incentives. This is true in a general and theoretic as well as in an electricity-specific sense. Studies are often limited to the monetary incentives but neglect other, non-monetary costs and benefits of demand response. [8] list divers factors, for example the medium or communication tools used for the announcement of events or dynamic tariffs, the time span between announcement and entering into force, incentives to choose flexible tariffs, automation, appliance stock, commitment, etc. Economic literature subsumes indirect monetary and non-monetary costs as opportunity costs [9] or, in a more specific manner, as hidden costs [10].

Realisation of demand response potentials

It is not possible for all customers to equally contribute to demand response. In the suggested model a stepwise reduction of potentially contributing customers is assumed. First, customers have to choose the tariff or must not be able to refuse the tariff. When the tariff is applicable, second, the customers need to have technical (e.g. appliances) and organisational (e.g. attendance) potentials to act in accordance with the tariff. Third, those customers left have the economic and social intention and willingness to act in accordance with the tariff. The steps of reduction may be assorted in a different order.

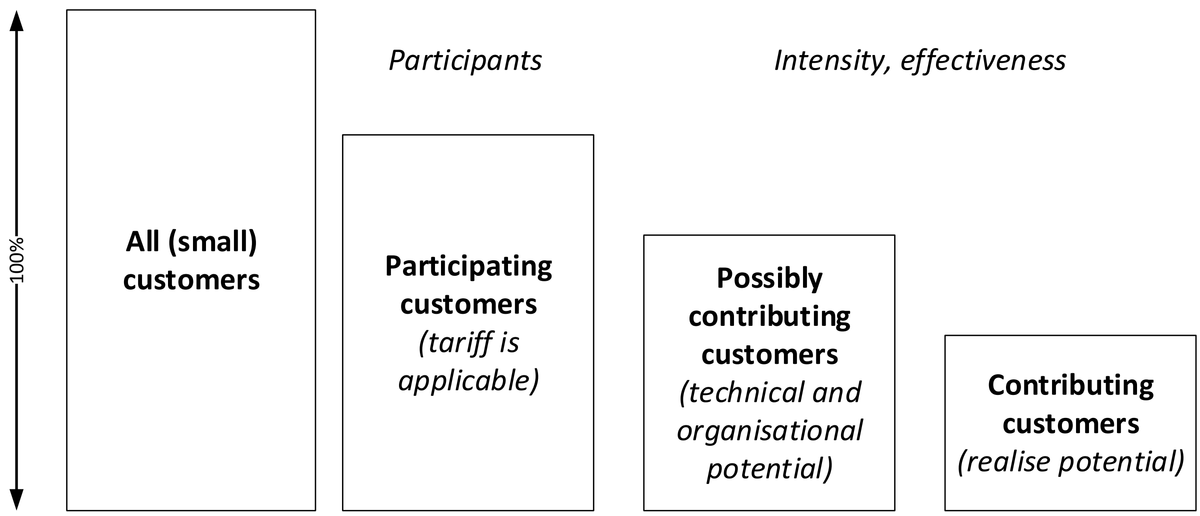

Figure 2: Model of reasons for the stepwise reduction of hypothetical contribution from all customers to contributing ones. Reductions may occur in another sequence or in parallel.

Retailers' pricing models are freely chosen by customers making a rational decision considering all (expected) monetary and non-monetary benefits and costs. People who do not choose the pricing model do not and cannot (due to a lack of information) act in accordance with the incentives[1] of the

[1] For example, environmentally conscious customers who have the non-monetary incentive to primarily use renewable energy cannot act in accordance with renewable generation (which goes – ceteris paribus – hand in hand with a lower spot price) due to lacking information.

pricing model. In accordance with most European regulation schemes, all customers are confronted with the same network charge models (‘participants’ in accordance with figure 2). Individualised charging models are not investigated in this analysis but may contribute to higher effectiveness and target orientation. Such individualised tariffs are accompanied by higher administrative and also marketing costs and legal issues (equality of treatment). Being confronted with a regulated network tariff model, all customers automatically are subject to the tariff model.

Nonetheless, regulation or legislation may allow more specific tariffs. However, given predefined conditions (load, network level, etc.) these tariffs may be chosen by every customer. For example, the German ‘Abschaltverordnung’ defines a legal exception from the normal regulation scheme for the case of large customers. Austrian regulation also schedules tariffs for interruptibility which can freely be chosen by small customers at the lowest network level. It should be noted that the assumption of an interruptible tariff offered to all customers does not imply that all customers choosing the tariff need to be interrupted at the same time.

In a second step, potential is reduced to those customers with technical and organisational potentials. They may need compatible appliances, storages (e.g. hot water storage) and ideally have automation or programming tools. Customers do not face organisational barriers (necessity of presence) or other concerns (operational reliability of appliances). Finally, in a third step customers weigh between monetary and non-monetary benefits on the one hand and losses of comfort and opportunity cost (time efforts) on the other hand. Economic effects (income) and social effects (own behaviour or character, expectation of others, e.g. your small child) will affect the customer’s decision. Again, this decision is rational (but it is also taking into account the opportunity costs of breaking routines).

Monetary and non-monetary benefits and costs

All possible monetary and non-monetary benefits and costs can be assigned to one (or more) of these three steps. The following figure exemplarily lists the most important aspects found in [2], [6], [11], [12], [13], [14], [15], [16], [17], [18], and [19] or mentioned in expert interviews. They illustrate the decisions and relevant expectations leading to active demand response participation.

Acceptance of demand response = monetary benefits + non-monetary benefits - monetary costs - non-monetary costs

monetary benefits	non-monetary benefits	monetary costs	non-monetary costs
Net value of • Lump sum payments • Reduced kWh-dependent netowrk charges • Reduced kW-dependent netowrk charges • Energy price savings • etc.	• Social compliance • Social image • Own image • Ecological contribution • etc.	• Communication tools • Appliances & equipment • Automation & capacity for automation • Storages (heat) • Storages (electricity) • Storages (space) • etc..	Losses of comfort • e.g. indoor temperature • e.g. happyness of family members Time requirements • to understand tariff information • for installations • for manual reactions • for behavioural changes • for programming devices • for automating processes • etc.

Figure 3: Monetary and non-monetary benefits and costs resulting in the acceptance of tariff models and active participation in demand response.

In the following, a brief literature review lists important aspects and factors of customers’ willingness to participate in demand response and act in accordance to a flexible tariff model:

The authors of [6] find out that customers avoid risk and complexity. Conventional tariffs with fixed costs per kWh are preferred by about 70% in comparison to a dynamic tariff. Female respondents show a slightly higher tendency towards conventional tariffs. Customers doubt the integration of renewable energy and that monetary savings can be achieved. Static time-of-use tariffs are more accepted and, in general, acceptance decreases with higher dynamism. If dynamic tariffs without fixed kWh price levels are compared to dynamic tariffs with three kWh price levels and a time-of-use tariff, and maximum price spreads can be chosen, than [12] again show that lower dynamism is preferred. In addition, [12] show that automation is preferred to manual reaction. The authors of [6] also figure out that, in average, annual monetary savings between 65 and 120 Euro are necessary to incentivise German customers to switch to a flexible tariff. Information about further customer or market segmentation is not provided.

These findings imply that there still is a group of people willing to accept and act in accordance to flexible tariffs although, on average, risk adversity is certified. Automation obviously reduces (expected) opportunity costs. It network tariffs are obligatory and regulated and thus applicable to all customers, these results nevertheless indicate the willingness to participate and act in accordance with the tariff scheme.

Field tests demonstrate the effectiveness of flexile tariffs although demonstrated effectiveness is always limited to these groups of customers who accepted and applied these tariffs. Moreover, these customers mostly accepted the tariffs for a short time span, are given bonuses and possible financial losses are settled by the field test team. However, from a qualitative method's point of view, field tests allow drawing conclusions on impact factors and hindrances. Qualitative results from [11], [17], [18], [19], [20], and [21] (cf. [12] for a summary) are:

- customers develop routines (indicating higher reaction to static tariffs),
- they react more to higher price spreads,
- they react to dynamic and event prices,
- they react more if automation is possible or 'enabling technology' is available,
- they react more if demand response does not directly decrease comfort,
- they also react if demand response does decrease comfort,
- they react more to more seldom events,
- they react more if storages are available.

As described above, [8] would complement the list with the following aspects: communication tools used for the announcement of events or dynamic tariffs, the time span between announcement and entering into force, appliance stock, and commitment.

Methodological advantages and restrictions

As described above, the inclusion of a literature review and a microeconomic analysis as a basis for the interviews and the inclusion of all relevant stakeholders in these interviews result in high robustness of results. There are probably hardly any relevant technical, social, economic, regulatory or organisational issues not included in the study. The major restriction is the country-specific nature of the research as 85% of the interviews were conducted with Austrian stakeholders. Nevertheless, first, Austria faces similar problems like most countries with liberalised energy markets and pending smart meter rollout, and second, literature review and microeconomic analysis are not country-specific. Thus, in the view of the author, all or at least most results described here can be generalised for industrialised countries with liberalised electricity markets.

The microeconomic analysis conducted in [2] is theory-based and partly enhanced with statements from expert interviews. Qualitatively analysing a future topic, it was neither possible not intended to define optimal quantitative values, e.g. price spreads, tariff intervals, etc. The microeconomic analysis investigated the effect of tariffs and pricing models at the customers' side; technical, organisational or legal feasibility within the scope of the retailer were not included.

General results

Network tariffs need to be comprehensive

Expert interviews and literature research in [2] show that new (dynamic) electricity pricing models will primarily address certain target groups. Due to the qualitative research style the authors were able to describe characteristics of persons within these target groups but could not quantify the share of these groups within the whole customer population. Target groups are described as being environmentally conscious, image-oriented, technology-friendly, cost-oriented, and in general more 'interested' than average people.

In contrast to pricing models which are freely chosen by interested customers, most network charges are regulated and network tariffs affect all customers. All customers of course include customers without technical demand response potentials or without demand response potentials due to their social environment (e.g. families with babies). These groups cannot react to new network tariffs and may be worse off (but they may be better off too). Experts agree that changes in order to achieve cost-reflective and target-oriented tariffs will always leave some worse and some better off. They state two claims: First, the transition should be executed slowly to allow for adoption measures. Second, as network tariffs affect all customers, tariffs need to be comprehensible for all customers, including the most vulnerable ones.

Comprehensibility implies, first, that the connection between the actions of customers and their network charged paid must be understandable. As tariffs become more difficult, comprehensibility of bills is often contradicted by transparency. Transparency of bills means that all parameters leading to the network charge paid need to be explained. Confronted with a bulk of information, bills are hardly understandable for (small) customers. Comprehensibility further implies, second, that the customers must be aware of how to influence the bill. Especially for the case of load tariffs this cannot be guaranteed.

Network tariffs need to be effective

Network tariffs should be cost reflective in accordance with the costs-by-cause principle. Customers causing certain network costs should pay for these costs. However, tariffs also need to be effective i.e. target-oriented. Thus network tariffs should incentivise customers to decrease the costs they cause and should also be incentivised to pursuit all strategic targets defined.

Tariff-specific results

Load tariff (kW-based)

Load tariffs measure the consumption in a predefined interval (e.g. 15 minutes). Rarely, measurement really focuses on actual loads. Maximum 15-minute consumption in a certain period (e.g. 1 month) is used for billing. This tariff incentivises customers to flatten their load curves or keep their loads below a certain level and to avoid individual peaks. Network operators may hope for better planning of small customer loads and network requirements. Customers would pay cost reflective network tariffs as customers with higher loads would contribute more to network infrastructure. If load tariffs are effective they are also target-oriented concerning the strategic targets of network reliability and avoided network expansion.

Small customers do not have information about their current load as the current load includes not only the room and appliances a certain person is in but also all the other rooms and appliances which are not observed by the person. Visualisation systems are not effective if they are not installed in all rooms and experts doubt people's acceptance of visualisation systems in all rooms. Automation which is exclusively oriented on current loads may lead to significant reductions of comfort. Small batteries or other storages (e.g. thermal storages) may lead to significant costs and decreases in energy efficiency. In most European countries average customers are not aware of loads of individual appliances and thus do not face the incentive or possibility to flatten their load. Another opportunity to enforce load limits without relying on the customer's awareness is to switch off the power supply at the customer's meter. For example, in Italy, residential customers are supplied with a contracted load of 3 kW. Households may consume 3.3 to 4 kW for 3 hours or more than 4 kW for 4 minutes before the meter automatically switches off the power supply. Power supply is restored with a button located on the electricity meter.

The usage of most appliances of small customers is stochastically distributed over time. Flattening individual loads would thus imply that many processes which have been done in parallel yet are then done one after the other. However, they are still done in the same period of day (e.g. in the evening). As processes were stochastically distributed before, loads are now longer and flatter but still stochastically distributed, leading to the same result in higher network levels. Lower network levels are anyhow only affected by marginal additional distribution losses. Experts state that positive effects due to flatter individual load curves may be achieved in rural areas with rather weak network capacities.

Time-of-use tariff

Experts agree that customers definitely understand the connection between switching on an appliance and the appliance consuming electricity which they pay for. For realising this connection, exact appliances' loads do not need to be known. Static predefined prices or network charges in predefined periods allow for developing routines and are applicable for the whole population. Peak loads may occur at classic times of a day (e.g. midday, evenings). Then, conventional time-of-use tariffs which focus on these times may contribute to flatten load curves by shifting consumption to other times of day.

Bearing in mind that the integration and use of renewable volatile generation is a strategic target, static time-of-use tariffs may set counterproductive incentives. PV generation peaks sometimes occur midday, sometimes not at all. Wind generation peaks occur on an even more volatile basis. When generation peaks occur, DNO are interested that these energies are consumed in order to sustain power quality. During generation peaks, high time-of-use tariffs send signals which fit neither to network nor market interests.

Experts realise that time-of-use tariffs may theoretically contribute to delayed or avoided network extensions. Nevertheless these experts state that, in practice, extensions are primarily driven by structural network congestions and demographic changes. Summing up, the target-oriented effectiveness of time-of-use tariffs probably is small although it is applicable to a broad majority of the customers.

Lump sum tariff

According to the assumptions made in [2], lump sum network tariffs are yearly network charges in dependency of *contracted* loads. This consumption-independent fixed network tariff may reflect customers' willingness to pay for the general availability of electricity from the grid at any time. This is also true for so-called prosumers with e.g. PV who would not contribute a 'fair' share for the network performance reserved for them.

Customers' decision on consuming electricity at a certain point of time depends – ceteris paribus – on the total price of electricity (energy + network). Fixed kWh-based network charges thus decrease the price spread customers perceive from the wholesale markets if they have chosen a dynamic priding model. Lump sum tariffs do not influence this price spread. Customers can freely react to market prices but do not at all have to care about the network's status. Actually, this means that the network is to be prepared for any action of the customers. However, being aware of the containing effect of kWh-based tariffs, this is also true for any currently primarily kWh-based network regulation. A pure lump sum tariff exhibits marginal network costs for an additional kWh of zero. Thus, customers are likely to consume more electricity.

Summing up, lump sum tariffs accord to the targets of volatile renewable integration and cost reflectiveness, but do not contribute to power quality, avoidance of network extension and energy efficiency.

Event tariffs

Event tariffs are irregularly announced phases of high prices and last between some hours and one day. They are also known as critical peak pricing or extreme day pricing. Results of a meta-analysis of field tests in [20] show that event tariffs achieve high participation and high efficacy with up to about 50% consumption reduction during the announced time span. In combination with other network tariffs (i.e. the above mentioned ones), event tariffs could obviously provide significant contribution to short-run (power quality) and long-run (extension avoidance) network interests. Experts point out that event tariffs could positively affect large-area network stability; however, network problems occur mostly in small-scale sections. Then, first, it is inappropriate to announce events for the whole network area. Second, event tariffs cannot reliably be used in small-scale sections with only few customers due to a (probably) high variance of customers' reactions.

Switchable loads tariff

This tariff is intentionally denominated 'switchable' instead of 'interruptible'. In many industrialised countries, interruptible load tariffs are offered or obligatory. DNOs are able to switch off loads connected at the individual customer's second meters. Normally, second meters connect heat pumps, storage heating, boilers, air conditioning, etc. and interrupting these loads does not immediately result in losses of comfort. However, smart grids may demand to increase loads. Not interrupting the connection does not automatically mean that the connected appliances consume electricity. Real 'switchability' may contribute to the integration of volatile decentralised energy sources and sustaining power quality.

In the case of dynamic or event tariffs prices or time spans are announced the day or at least hours before they enter into force. Especially if short-run network problems occur, these tariffs cannot contribute to sustaining power quality. For the case of a switchable loads tariff, the DNO is permitted to switch on or off the appliances in return to e.g. lump sum payments. With this tariff, interventions of the DNO are possible almost real-time. Results from the German E-Energy program suggest that small customers' switchable appliances do not offer enough flexibility to overcome e.g. congestions [21], but experts consider (even only) interruptibility of loads as essential for future network stability.

Energy service

Microeconomic analysis suggests that the co-ordinated delivery of energy services is optimal for all strategic targets. The interest of DNOs are respected, market signals can mostly be followed and cost minimising suppliers guarantee efficiency of appliances. However, co-ordination is complex in liberalised markets and leaves open many regulatory and market design questions. Without co-ordination, energy services are similar to interruptible tariffs or dynamic pricing models.

Dynamic tariff

Dynamic kW- or kWh-dependent tariffs alternate in dependency of actual or expected network capacities. The analysis in [2] elaborates that dynamic network tariffs are not appropriate in practice: First, 'real' dynamism (i.e. not time-of-use) appears as an 'unsolvable' regulatory and administrative effort. Second, scaling down regulated tariffs to those small-scale network sections where it is needed means high variance and unpredictability of customers' reactions and methodological efforts which bear no relation to administrative costs. Third, although increasing decentralised volatile generation will increase the number of critical events, experts nevertheless expect them to be 'seldom'; seldom events can equally be handled with event tariffs which are less complex. Last, the German regulatory authority considers two dynamic elements (dynamic pricing models, dynamic network charges) as being too complex to be clear to customers in all situations [22].

Limited free consumption (contingent tariff)

Microeconomic analysis suggests that defining the free contingent is complex and may lead to counterproductive incentives. Retailers and DSOs hardly know their small customers, i.e. they do not know the size of a household or the number of employees in an office-based firm. Thus, they would need to apply a one-size-fits-all contingent. However, for example, a contingent of 1,000 kWh is high for a single person household but low for a five person household. Customers consuming less than the threshold are likely to try to consume the full contingent and increase their consumption. Thus, the threshold should be set at a low value. Those network costs not covered below the threshold need to be covered by the consumption above the threshold. Distributional effects leave customers with higher consumption worse off. Contrariwise, a low threshold implies a relatively low sum of network costs carried over to the kWh-tariff above the threshold and, therefore, only a small increase compared to the usual tariff. Consequently, energy conservation efforts decrease.

Depending on the threshold, the contingent tariff either does not offer high efficacy or is ambiguous with regard of the effects: the tariff sets incentives for smaller customers to increase consumption and for larger customers to decrease consumption. The qualitative research methods cannot indicate which effect is stronger.

Progressive consumption tariff

Progressive tariffs continuously or stepwise increase the kWh-based network charge. Obviously, a contingent tariff is a specific case of a progressive tariff with an initial charge of zero. If the stepwise increase is not too high a progressive tariff may incentivise energy efficiency without putting a high burden on customers with high consumption. For example, Italy's volume-dependent network tariff defines thresholds at 1,800 kWh, 2,640 kWh and 4,440 kWh. However, the lowest kWh tariff is only 10% higher than the highest one. In similarity to setting the threshold, the ideal trade-off between efficiency on the one hand and social acceptance and customer comprehensibility on the other hand remains unclear.

Recommendations

The following recommendations on optimal network tariffs for small customers are applicable for fully liberalised electricity market without smart meters being installed but roll-out of smart meters is expected to be finished in 2020. Thus recommendations are applicable for most EU countries. The recommendations are derived for the sort run, before smart meters are rolled out, in the medium run, when roll out will be completed and pricing models are expected to have arrived at the market (year 2025), and in the long run, assuming extensive automation and ICT in the electricity system.

Short-run optimisation of network tariffs

Without smart meters being installed frequent measurement of consumption or loads is not feasible. As suppliers cannot bill actual prices and will not offer any according pricing model, customers cannot react to current generation volumes or wholesale prices. Consequently, network tariffs cannot disturb any market signals. Tariffs can thus be designed to exclusively aim at the DNO's interests.

Although lump sum tariffs may be regarded as being in accordance with the costs-by-cause principle, without smart meters, it cannot positively affect customers' reactions to the market side. Moreover, it negatively affects the DNOs' interest as it does not incentivise a low volume or a certain time of consumption.

According to the costs-by-cause principle, billing should primarily be based on actual loads; however, measurement of actual loads is not feasible. The remaining opportunity is to negatively incentivise any load which is achieved with kWh-based tariffs. Generally, the strategic target of energy efficiency is best achieved by kWh-based tariffs. KWh-based tariffs decrease consumption at any time and thus (at least partly) contribute to a decrease of loads.

In the short run, network charges should exclusively be billed on a kWh basis.

Medium-run optimisation of network tariffs

With smart meters being rolled out, suppliers are expected to offer dynamic power pricing models and target groups are expected to accept these. Additionally, measurement of actual (peak) loads is possible. Target-oriented network tariffs should be designed to weigh out the interests of the network (power quality, avoidance of network extensions) and the market (being able to pass on full price spreads).

In the phase of transition, a lump sum tariff should be combined with a kWh-based tariff.

Lump sum tariffs do not decrease the price spread perceived by the customers. Thus, they do not hinder the development and impact of real time pricing models which imply a more efficient reaction of the demand side. Lump sum tariffs are easily administrable, especially as small customers exhibit homogeneous requirements to the electricity network. Moreover, they do not require customers to have knowledge about their current load and the load of individual appliances which is regarded as a major problem concerning load tariffs. Lump sum tariffs allocate costs in accordance to the costs-by-cause principle as they reflect the willingness to pay e.g. of prosumers who have a network connection which has to be designed for usual use nevertheless prosumers consume less than average users.

However, lump sum tariffs dramatically decrease the costs of a kWh consumed. Total network charges should thus further be also based at kWh tariffs. In contrast to load tariffs, the action-payment-causality of kWh-based tariffs is well understood by small customers. Due to the qualitative research design, it is not possible to derive optimal shares of fixed and variable tariffs for e.g. an average household.

In the medium run, i.e. with smart meters but without extensive automation and ICT infrastructure, this tariff model may be ideal concerning cause-of-costs and target orientation. However, energy-intensive appliances (at the small customers' scale) like air conditioning or electric cars are not used stochastically but at the same time of day and for more than just a few minutes. These simultaneous loads may cause problems at higher network levels or require networks extensions. Further research needs to elaborate

- whether load tariffs are effective and efficient (lower network extension costs compared to higher administration costs),
- which intervals are optimal and feasible for load measurement (peak consumption in kWh per h, kWh per 15 min, etc.),
- which intervals are optimal as billing period (weakly peak load, monthly peak load)
- which communication tools enable small customers to realise high load values (SMS, standardised calls, smart phone apps, ambient equipment, …)

Long-run optimisation of network tariffs

(Only) with smart meters being rolled out and automation and ICT being wide-spread ('smart homes', 'smart offices', 'smart buildings' …) real smart/intelligent interaction of markets and networks is feasible and it is thus possible to define procedures if conflicting interests arise. [23] defined the so-called 'traffic light model', with free market interaction of customers with retailers or third parties when the network status is okay (green phase), interdicted market interaction if network status is not okay (red phase), and limited interaction in the orange transition phase. Literature review and expert interviews clearly revealed that a likewise model is appreciated by all stakeholders but neither literature nor interview partners can offer clarity on parameters and criteria, how the status is defined, defined by whom, communicated to whom, and with which lapse of time. Summing up, research is needed to define long run criteria and network tariffs more precisely.

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Development and Implementation of Tools to Improve the Possibilities of Demand Response on Residential Customer Segments

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Abstract

Residential customer segments represent about 25% of the final demand of electricity in EU. Unfortunately, the possibilities of Demand Response are very limited in these segments at present. Some barriers are: the specific legislation in each country, technical complexity of response and the education of customers about electricity markets. This work intends to provide tools (simple and with a reduced cost) which could be used to overcome some of the abovementioned barriers and help the customer (directly or through an aggregator) in its participation in these initiatives. Some tools have been included in a prototype of monitoring and control system including some interesting capacities for the consumer. First, data can be exchanged from or to the management system of the aggregator (for example, to receive load control possibilities extracted from Physically Based Load Models, or, to obtain the disaggregation of its demand to know the consumption and cost per end-use). Second, the customer can manage and extract the measurements from "conventional" smart meters. Moreover, some links to the external databases (aggregators, ESCOs, System Operator (SO), Weather Agencies) are allowed. Third: the system has the ability to control some loads (plug in devices, programmable controlled thermostats, dimmers,..). Finally, the customer can perform a simple load forecasting to adapt its demand to price allowing demand elasticity. These capabilities have been implemented in a prototype. Field experiences are also presented and they demonstrate that the proposed system could provide information enough and practical measures to achieve energy cost reductions up to 10%.

1. Introduction

The proposed rising share of non-predictable generation by 2050 in the European Grid increases the need to improve both flexibly in demand and supply sides to face to this less flexible green generation. The lower predictability in the market and network operations implies an urgent need for operable customer flexibility to cope with this volatility. From the economic point of view, it is necessary to optimise the investments and operational costs involved in upgrading the future European Electricity Networks to include this new "mix" in generation. For years, the attitude was just throwing more supply resources at it. That simply does not work anymore. In some of our electrical systems, the peak demand events occurring for less than 1 per cent of the time per year, account for around 25 per cent of retail electricity costs [1] and a lot of networks are still planned according to the peak events because the potential of the demand-side is not considered. These methods should change in the future to avoid unnecessary investments and political authorities are aware with the problem. For these reasons, some incentives for the demand-side are being included in the EU. For example, the article 15.8 of the Energy Efficiency Directive (2012/27/EU) [2] enables the Demand Response (DR) participation in wholesale and retail markets, including balancing and ancillary services with the objective of removing the barriers for a broader deployment of Energy Efficiency policy (the term is rather cloudy in CE documents, including usually DR in the portfolio of Energy Efficiency). Technical specifications for participation in these markets must include the participation of aggregation (i.e. allowing that small customers become engaged in DR) "…in a non-discriminatory manner, on the basis of their technical capabilities". This objective is commonly admitted in other advanced economies on DR [3].

The solution of this problem needs a rational development of new and less expensive resources to ensure cost-effectiveness for these investments, but not often necessary from a material point of view (e.g. new software tools, information, education,…). It is also possible to take into account new solutions that are cost effective when synergies (economies of scale) are developed between energy policies: the integration of Energy Efficiency, Demand Response (EE&DR) and ICT technologies [4]. The deployment of the new "smart meter" generation in the next decade planned by EU-28 or the USA is an important measure (the objective of the European Commission support policy on Energy is that by 2020 [5], 80% of consumers have these smart devices) and involves investments between €30 and €40 billion. The premise is that technology is an enabling factor to the achievement of grid efficiency objectives and, in this way, its modernization justifies this huge cost. This assumption is based on the results of some research projects developed in the last decade, for example in the USA [6], and specifically focussed on small and medium users. These pilots show that technology significantly removes barriers, increases the response of the customers [7] and achieves the reduction of their energy costs. In this work, the centre of attention is focused on residential customers, but the results could be replicated on other small-size resources because they represent near 37% of the overall demand (EU 2012 [8], including commercial segments) and they basically remain "unexplored".

Unfortunately, these results from pilots sometimes conduct to an erroneous trend: new technologies are what decide alone the successes of programs. A recent survey of European Smart Metering Industry Group (ESMIG, [9]), states that "… unless a technology is equipped to act as support to customer engagement, it will not create savings or improve systems efficiency…". This report analyzes pilot projects on Demand Response and Energy Efficiency worldwide and for instance it concludes that "…this also puts in question the current tendency to emphasize technological development over and above other factors in European pilot schemes …". About the results on energy conservation, the maximum potential is reached in "in house displays" (IHD) pilots with an 8,7% (this result is far from 20-20-20 objectives of EU, see Table 1 [10]). The problem is that the potential of smart metering may not benefit the consumers nor the grid if customers are not well informed about the advantages of these technologies [11]- [12] and the possibilities that enable the use of technology to participate into the markets. These customer segments stand for 25 to 40% of the overall electricity demand in EU-28, and the unexploited potential for efficiency can reach up to 16% [13]. Therefore, more knowledge and experience has to be acquired and new information made available with the deployment of smart meters and "enabling" technology in the EU and USA. This integration is foreseen in the prototype described in this paper.

Table 1. The EU 20-20-20 targets by 2020 and its achievement [10]

Objective	Current trend to 2020	Status
Reduce greenhouse emissions	20%	√
Increase the share of renewables	20%	√
Reduce energy use	10%	X

Another common mistake is that the savings potential is not achieved due to markets failures. The EU Commission in [7] says that "… due to low price elasticity of some sector, e.g. residential one, price signal are not always a solution for the change". It is very difficult to find and develop an "elastic pattern" in the demand for electricity (energy) if price for small and medium users does not change and does not reflect the costs for the society. This paper tries to demonstrate that price-elasticity is possible if the customer has information and decision tools (e.g. change of end-use behaviour, selection of a tariff,…). Notice that the capacity of small and medium users is far from their maximum potential [13]). Major improvements in elasticity can be achieved with education, customer feedback and tests of policies in customer segments with a great potential for Energy Efficiency and Demand Response (EE&DR).

Another barrier for the user is that electricity companies and retailers in the EU have limited experience in selling complex services to their smaller residential and commercial customers (e.g. DR products) [14]- [15]. This fact is a barrier for the customer and aggregator, so they need additional tools to engage them in DR. Consequently, EU customers have to overcome the most complex barriers to actually obtain the maximum potential out of DR&EE: education and technical matters. This paper attempts to present tools that integrate ICT technologies but also software tools that enhance the information received from these.

This paper is structured as follows: Section 2 introduces the prototype capabilities; Section 3 details the software structure; Section 4 presents some of the simulation results and, finally, Section 5 puts forward the conclusions.

2. The description of the system prototype: monitoring and measurement capacities

The basic idea of the prototype developed is to offer the customer and the aggregator the maximum flexibility to know their consumption, evaluate from it their DR potential and then give them feedback with respect to DR and EE policies portfolio. As stated before, ICT technologies are a DR&EE driver but other DR tools are needed: namely load modelling [16] and non-intrusive monitoring [17]. Each capability of the proposed system will be presented in the next paragraphs.

2.1. Energy and Demand measurement capabilities

As summarized in table 2, recent survey data [18] indicate that Smart Meter (SM) penetration rates and the number of these meters continue to increase in developed countries (USA, Canada, Australia or the EU). In the USA the penetration in residential sectors is slightly greater than in commercial or industrial segments (about 30.4% in 2012). For example, Edison Foundation's Institute for Electric Innovation projects more than half of all U.S. households will have advanced meters by 2015. According to CE estimates, their policy represents the installation of about 195 million of smart meters by 2020 for electricity (ca. 70% of EU-28 consumers) and an accumulated investment of €35 billion.

Table 2. Estimates of Advanced Meter number and Penetration Rates in the USA [18]

Data source	Data as Of	Number of SM (millions)	Number of meters (millions)	Penetration rate (% of SM)
2008 FERC	Dec 2007	6.7	144.4	4.7
2010 FERC	Dec 2009	12.8	147.8	8.7
2012 FERC	Dec 2011	37.7	166.5	25.8
2012 Form EIA-861	Dec 2012	43.2	145.3	29.
Edison Foundation	July 2013	45.8	145.3	31.5

The future of smart metering will be bright, but from a practical point of view is quite possible that the customer does not have yet a smart meter, or they do not have access to detailed meter data, or if they exist, it may have an issue of data confidentiality between the commercializer of energy and the aggregator. Finally, some evaluation protocols for Energy Efficiency suggest (for example, due the seasonality of energy usage) that some loggers may be placed on energy-efficiency appliances in a random sample of customers **[19]**. In this way, the access to demand data is a cornerstone in the proposed system.

a b c

Figure 1. Demand and Energy meters: a) Smart Meter (Three phase Sagemcom CX2000-9), b) Electricity Digital Meter (Three phases Voltcraft), c) Clamp power meter (Aeon Z-Wave).

To take into account these problems, the proposed system has the following abilities: allows the reading of the optical output of the customer energy meter (e.g. Figure 1.a) through a Light Dependent Resistor (LDR). These LDR sensor readings have been done through a microcontroller board based on Arduino Uno **[20]**. This board can read another data of interest such as temperature or humidity. The exchange of data from the Arduino to the PC (customer or aggregator) was performed using XBee modules (Digi International). These communication cards have a range of 90m indoors and 3,000m outdoors. In the case that customer has an own meter (Figure 1b) the procedure is similar but in these cases the system directly records the electric pulse output of the meter (in our case, 500 impulse/kWh). If the customer meter is not accessible for measuring the optical output, or it has not got an electronic counter in its home, the easiest and cheapest option (around €100 for a three-phase unit) is to install a meter with current clamps (Figure 1c) with transmission capability of signal. In our case, the power meter has an emitter, which sends information to a PC through an USB Z-Stick using Z-wave protocols (with a cost about €50).

2.2. Links to external databases

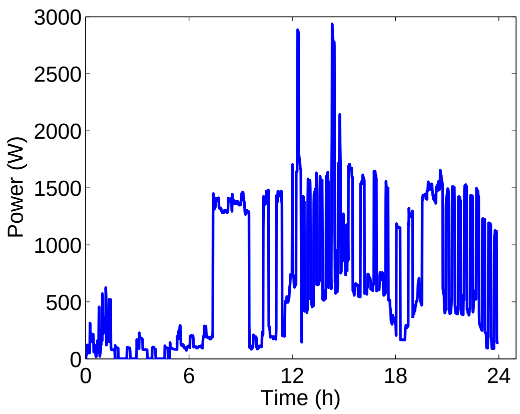
Another ability of the system (from the point of view of software) should be the access to external databases, for instance: from aggregators, Energy Service Companies (ESCOs), System and Market Operators, Weather Agencies, etc. Temperature and humidity are data that can condition the use or rescheduling of some end-uses. Besides, the aggregator needs these data to evaluate demand baselines or to run load simulation software. In other cases, it is necessary that the customer knows a forecast about the energy cost in the near future (usually day-ahead) to respond to Time of Use (ToU) or Critical Peak Pricing (CPP) options. In the future, and to engage the customer in load response to price policies, the customer should receive and manage (alone or probably with the help of an aggregator) feedback from the electricity markets (DR event signals, price signals,…). For demonstration purposes the system is able to receive weather data from AEMET (Agencia Española de Meteorología, Spain), and it recovers every afternoon day-ahead price for small customer segments (available but not mandatory since 2014 in Spain) through the web platform “e-sios” of the Spanish SO (REE) [21].

2.3. Feedback possibilities from the aggregator

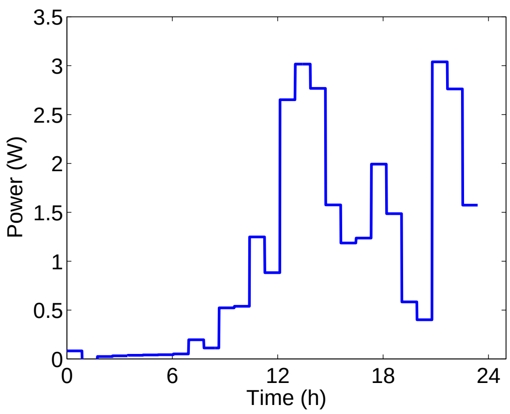
An important issue regarding customer engagement in DR policies is that, up to now, the European approach to DR&EE policies is to establish higher minimum power levels (to be considered for the qualification of DR resources, for example 2MW in UK Capacity Markets) than the minimum qualification level established in the USA (from 100kW to 500kW). This threshold is expected to be progressively reduced but the aggregation of small demand segments is still necessary (the proposal of regulators is 250kW for rated capacity). Anyway, due to the intrinsic complexity of electricity markets and ICT technology (e.g. energy efficiency, load control, risk analysis) it is necessary that a third part (the aggregator) manages the customer load and performs information and support tasks because a greater price response engagement is an objective of some ISO worldwide, see PJ; White Paper [22].

To achieve this concern, the data acquired by smart or electronic meters (see paragraph 2.1) should be exchanged from the customer PC to the management system of the aggregator and vice versa. For example, the aggregator can evaluate the load control possibilities analyzed from Physically Based Load Models (PBLM) [16] according to customer end-uses and characteristics (weather, location,...). The user could have feedback with respect the results of different direct control actions on comfort and cost (for example in air conditioning and heat pump loads). Besides, customer and aggregator can obtain the disaggregation of its overall demand to more precisely known the energy consumption and cost per end-use, and consequently evaluate the possibilities of a change, both in behaviour and the retrofit of appliances by others with a higher efficiency.

Figures 2.a&b show a record of daily demand for two residential customers. These data (measurement pacer 1 min) are sent from the customer to the aggregator who performs the end-use analysis. Through non intrusive tools, based on Hilbert Transform [17], the aggregator can extract the daily behaviour of some end-uses, for example heating/cooling (H/C) loads (see figure 2b&d). The behaviour of this end-use informs about the possibility of taking into account some DR options (for instance, if the load demand matches system peak demand), or in other case, to reschedule the customer demand to take profit from the changes of energy prices. This tool can also be used to verify that a load control policy has been performed by the customer as requested.



a



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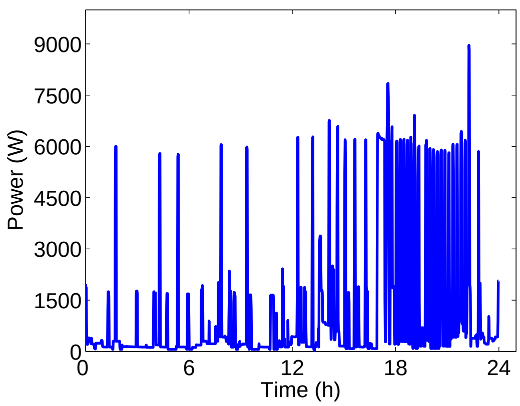

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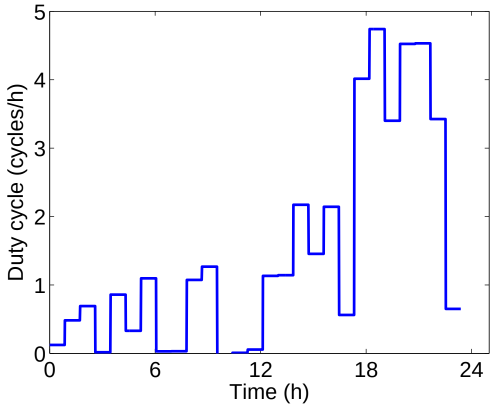

d

Figure 2 Overall daily customer demand (a&c) and the disaggregation of heating/cooling end-use, specifically duty-cycles, (b&d) evaluated through Non-Intrusive Methodologies

Taking into account the information shown in figures 2b&d, the aggregator explores the possibilities to control the HC load, in this case a conventional air conditioning load. If a DR event is called by SO (for example from 13 to 16h), the possibilities are to shedding load or to apply a forced duty cycle (in this case two reductions of 40&60% have been simulated). A PBLM simulator like the one presented in [16] performs this task (see figures 3a&b).The aggregator takes into account the lack of comfort (i.e. the growth of indoor temperature above thermostat set-point, in our case, see figure 3b, 23-24ºC) and proposes the customer the different possibilities: revenues and the effect in the temperature of each control policy. Theoretically, the system allows the implementation of the policy chosen by customer through the control devices. Notice that, in practice, the customer choice will be simpler than the abovementioned: the customer establishes a minimum level of comfort and lets the aggregator makes the choice of the best policy (revenues vs. comfort).

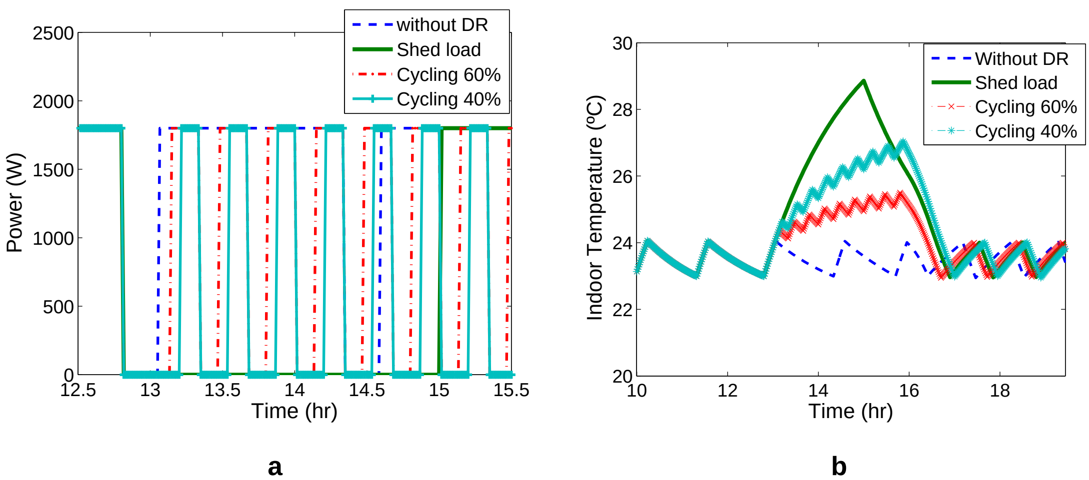

Figure 3. H/C end-use: a) Duty cycles with and without a load control policy; b) Indoor temperature before and after control.

2.4 Load control

Finally, the prototype should manage different end-uses. For example, it should perform the abovementioned duty cycles in H/C, the control of lighting, indoor temperature, etc. For simplicity, availability and cost concerns, the hardware being used works under FS20 protocol [23]. That is a wireless protocol (unidirectional) that manages plugs, dimmers and thermostats (for electric and thermal loads). Some examples are presented in Figure 4.

Figure 4. FS20 devices: a) Radio Switch module for DIN rail (16A); b) Controllable plugs; c) Controllable thermostat

3. Energy Control System Software

The energy control system software developed for the prototype has been installed on a PC and receives external data as stated in previous paragraphs. These data enable the program implemented in the PC can perform the management of electrical loads and therefore, automatic control when different DR program signals are received. The PC sends real-time information for display on different devices, such as computers, tablets, smartphones, etc. These devices also allow changing the configuration of the control system manually, such as a change in the thermostat or turning on a load that had been automatically switched off by the energy control system.

The PC receives data from four different sources: internet, smart meter, aggregator software, customer and loads. These data provide information about DR program signals (hourly electricity prices and control signals to lower consumption such as grid constraints), demand monitored in real time, load status (on or off) and individual variables of each user which are configured through a web interface. Next figure shows energy control system inputs and outputs.

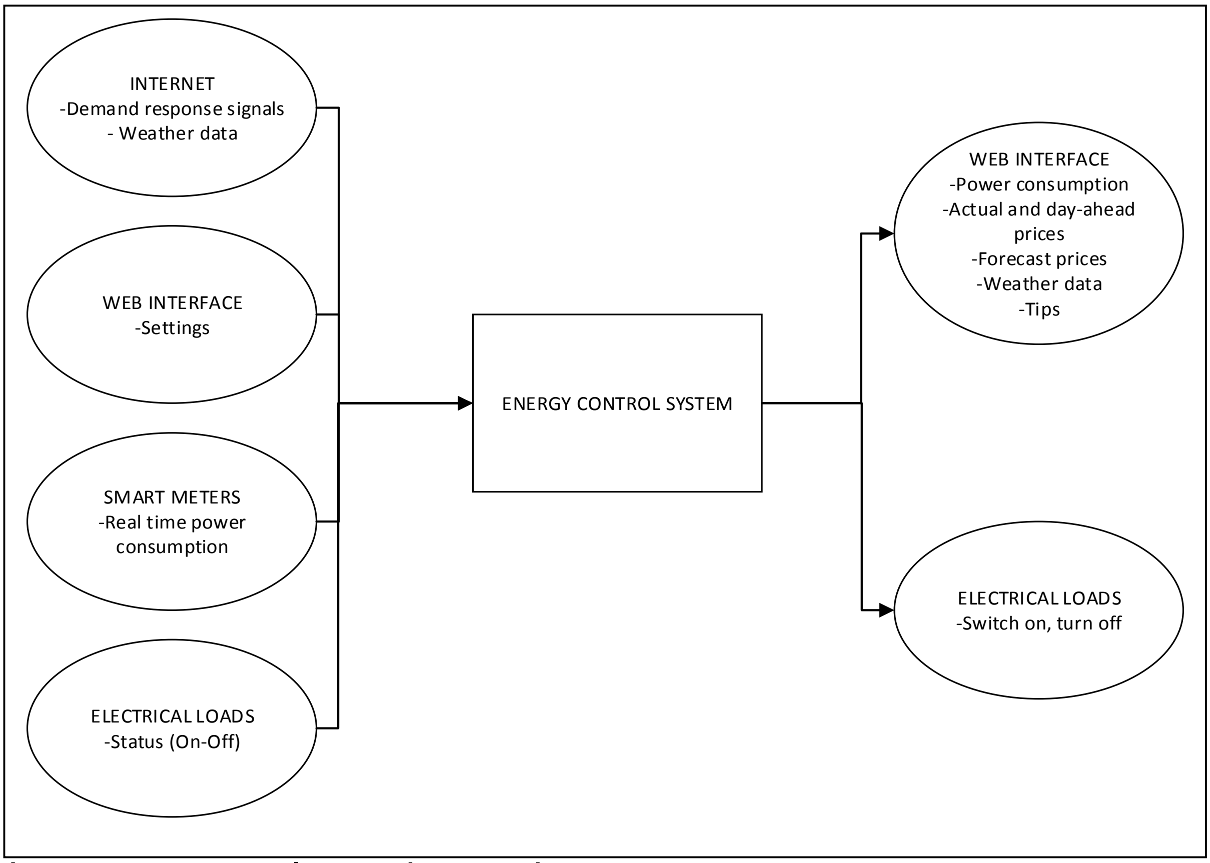

Figure 5. Energy control system inputs and outputs

Data inputs are managed by IpSymcon software [24], which facilitates the automation of both the residential sector and the industrial sector. This software provides the following benefits:

- Allows integration of a large number of communication protocols in the same program such as FS20, HomeMatic, Z-Wave, ZigBee, EnOcean, ModBus and Siemens PLCs.

- Programming in PHP: This feature allows developing a program capable of downloading electricity market day-ahead prices, save load state variables and user settings and developing algorithms for load control.

- Automatic execution of the code: IP-Symcon allows the execution of programs in PHP (scripts) cyclically and when changes in variables occur. This facilitates the automatic download of electricity prices and control signals, updating user settings, etc.

The system outputs are connection and disconnection of electrical loads and providing the user information through a web interface, where the current and forecast tariff price chosen by the user, evolution and forecast of consumption and weather data are shown. It also has the possibility of downloading the data stored and finally show tips that would help users to improve their consumption profile.

The web interface has been programmed with HTML and has the following five tabs:

- Prices: Shows the user the actual, day-ahead and forecast electricity market price according to the selected electricity tariff.

- Consumption: Allows the user to view a graph showing the power consumption in real time and a forecast of demand that the user would consume during the day.

- Tips: Displays the user recommendations to improve their consumption profile, such as the cheapest electricity tariff and the best power to contract according to their consumption profile. Figure 6 shows according to the last three months user consumption, the price of three different tariffs and the best choice.

- Data: The user is able to access data stored.

- Configuration: Allows the user to customize the energy control system in a simple way, choosing the electricity tariff, the degree of automation (local or remote, i.e. an external such as the aggregator), electrical loads to control and data inputs such as the power contracted to make recommendations.

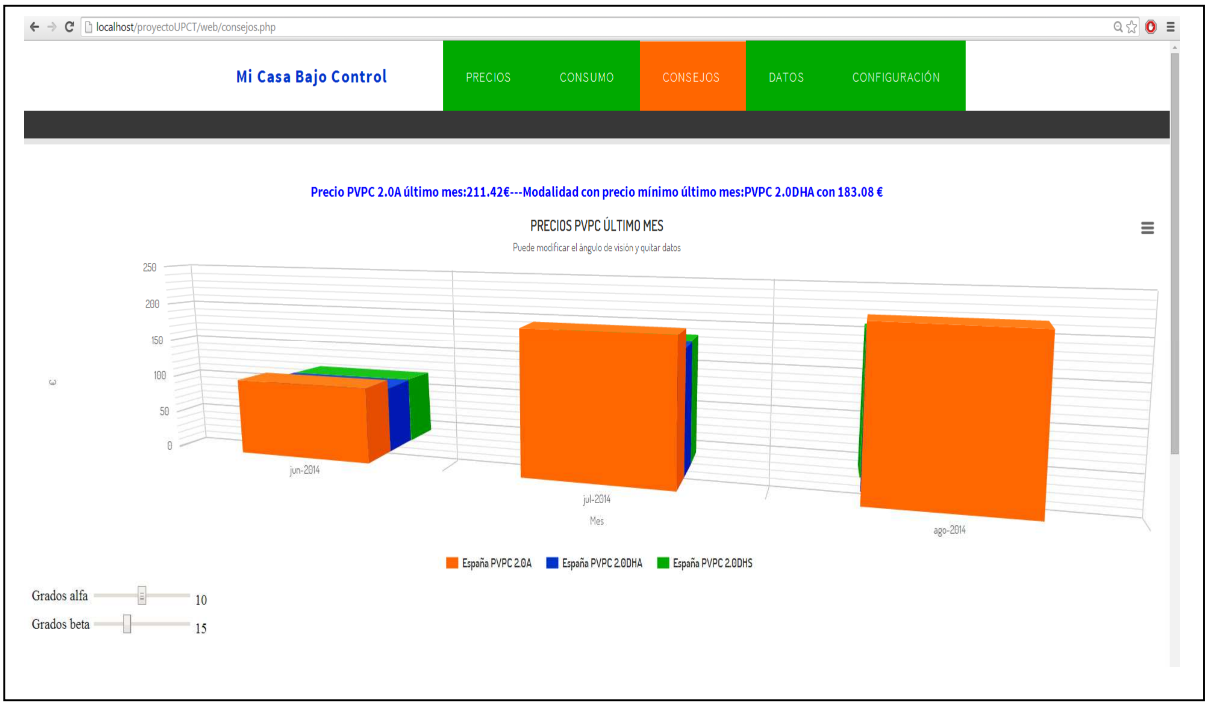

Figure 6. Web interface: last three months user consumption

4. Energy Control System: Results

The historical power consumption data of two real customers of the Southeast of Spain during the months of July and August 2014 has been studied to test the prototype. These data have been analysed in order to obtain the forecast error, a real thermal model application and the effect of switching-off the air conditioning due to control requirements. The average outside temperature during the test in July was 27.4 °C and 28.1°C in August. The customer had a tariff called PVPC 2.0A and the principal appliances were air conditioning, electric water heater, fridge, washing machine, dishwasher and television.

It has also been analyzed the thermal model outputs for different air conditioning controlled disconnection durations (see paragraph 2.3) and calculated the consumption cost, taking into account a real electricity price of 26th September 2014. The system integrates the overall information received from webs, aggregators, SO, and shows: the overall demand, savings compared to the non-controlled case and the different raises of indoor temperature depend on the disconnection durations (i.e. forced duty cycles, see paragraph 2 and figure 3).

Table 3. Thermal Model Application of Full Load Control (Shed Load) from 0 to 120 min.

Switching off time (min)	**0**	**20**	**40**	**60**	**80**	**100**	**120**
Daily costs (€)	2,44	2,43	2,38	2,35	2,33	2,32	2,28
Savings (€)	0	0,01	0,06	0,09	0,11	0,12	0,16
Savings (%)	0,00	0,41	2,46	3,69	4,51	4,92	6,56
Raise of temperature (°C)	0	1,34	2,46	3,38	4,15	4,79	5,31
Energy Payback after the control period (%)	0	99,39	97,54	96,31	95,49	95,08	93,44

It is shown in the results a range of savings among 1,34% and 5,31% related to disconnection durations between 20 and 120 minutes, while the rise of temperature range is kept among 1,34 °C and 5,31°C.

It has also been taken into account the experimental measured of the electrical energy that is needed by the air conditioner to extract the thermal energy gained in the house during an hour time stop of the air conditioner (i.e. the so called payback or snapback in the literature), which resulted in 44% additional energy consumption in the next hour. With the energy required by the air conditioner in the controlled period and the energy savings data, the real savings data related to this system implementation during the month of July and August have been evaluated (see table 4). It is shown the monthly price comparison of real consumption and consumption that would arise using the energy control system.

Table 4. Energy system air conditioning control comparison

Item	**July**	**August**	**Total**
Energy Consumption (kWh)	1594,43	1749,46	3343,89
Energy consumption with control (kWh)	1507,44	1727,22	3234,66
Energy savings (%)	5,45	1,27	3,26
Real time price bill (€)	186,28	211,42	397,7
Real time price bill with control (€)	175,54	201,12	376,66
Savings (€)	10,74	10,3	21,04

Savings (%)	5,76	4,87	5,29

The results show that savings of 5,29% of the total electricity bill would have been obtained applying control air conditioner one hour a day on those days that the air conditioner had been turned on. It has been analysed the data stored during the months of July and August to obtain the error that would appear in the daily power forecast comparing the day before power data and the week before power data. In the same way, the error that would appear in the hourly power data has been calculated taking into account the day before hourly demand data and the demand at the last week, see table 5.

Table 5. Forecast of mean absolute percentage error (MAPE)

	MAPE (%)
Daily power forecast using day before	15,59
Daily power forecast using week before	18,86
Hourly power forecast using hour before	51,17
Hourly power forecast using day before	115,37
Hourly power forecast using week before	114,61

Some studies [25] have shown that the simple method of forecasting based on the latest available data used (Persistent) is one of the simplest and most reliable methods, presenting better forecasts than other mathematical methods. It has been proved that the best estimation correspond to the earlier data (previous day for daily forecasts and previous hour for hourly forecasts). In addition, the more grouped the data are the smaller is the error (less error in daily forecasts than in hourly forecasts).

To reduce the absolute forecast error in the simple daily forecast method, daily temperature data have been introduced. The best results have been obtained taking the day before daily data when the temperature difference was minor or equal to 3°C and the week before daily data if other. Applying this condition it has been possible to decrease the absolute average error from 15,59% to 15,29% for the stored data during the months of July and August (average MAPE in [25] is 30%, which shows it is an acceptable error).Implementation of new forecast methods, such as those based on neuronal networks, could improve MAPE. The tests in [26] yield a MAPE from 2.32% to 1.84% in different sessions of the Spanish electricity market (35000 MW peaks of load).

5. Conclusions

Electricity customers can obtain interesting benefits from the energy management and trading with the help of an aggregator. The aggregator acts as an enrolling participant in DR Programs (driven by SO and DSOs). Unfortunately, it is difficult to directly participate in the electricity market due to its complexity for the end-user. This paper proposes the integration of tools (software and hardware) in a PC pilot system (cheap and easy to understand), where the customer or a third party agent (aggregator) can identify, simulate and evaluate different policies (DR&EE) to maximize its revenues. From the results of the simulations, and the effective engagement of ICT technologies, the customer can obtain the necessary information to decide: the best tariff option, the management or change in its behavior or, finally, join load-response programs. In this last case, applied to H/C loads only, DR policies provide interesting savings of around 5% with a reasonable comfort (indoor parameters).

Finally, the methodology presented in the paper provides tools for the effective integration of customers in the search for future new resources less expensive than “conventional” policies, i.e. the rule that demand follows supply.

6. Acknowledgment

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Load Shift Potential Analysis Using Various Demand Response Tariff Models on Swiss Service Sector Buildings

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Abstract

With an increasing amount of volatile renewable energy, balancing demand and supply becomes increasingly demanding. To achieve this balance, Demand Response (DR) is one important approach. DR needs a paradigm change from energy savings towards shifting electrical consumption to timeslots with excess energy generation, and from centralized network stabilization efforts to a price driven, decentralized approach. This change empowers consumers to act with load shifting (LS) on price variations, respecting their comfort, process and safety needs. In the residential area, the necessary building automation is not yet widely spread, therefore we use the Swiss service sector buildings (SSSB) as a model.

In this paper iHomeLab reports on investigations on DR and the according LS potential (LSP), focusing on SSSB. We base our LSP calculations on Swiss energy consumption data, broken down to distinct categories of electrical appliances. Further we consider the typical energy usage in different seasons, week- and daytimes. Four time-dependent tariff models are applied in a simulation to the load-curves in order to estimate the peak smoothing by load shifting at tariff peak times.

Our results show that 35% of the total energy consumed in the SSSB can potentially be used for LS. Significant seasonal and intraweek differences are observed. The air condition potential dominates in summer, whereas room heating is the main factor in winter. The summer LSP peak is 45% higher than the winter peak, but available only for 15 to 60 minutes, compared to several hours in winter. Analysing the size structure of SSSB shows that by rolling out DR to only the largest sites (7% of sites), already 65% of the LSP can be tapped.

Introduction

The electricity systems in developed countries worldwide are experiencing a fundamental transformation towards a more decentralized power generation with a growing share of renewable sources with fluctuating production levels as shown in [1]. Given the traditional centralized power generation regime, also grid stability and security of supply are in the responsibility of Transmission System Operators (TSOs) like Swissgrid and the Distribution System Operators (DSOs), which try to cut peaks and minimize balancing energy by using load clipping and Direct Load Control (DLC, i.e. remotely switching off loads during peak demand periods, as in [2], [3], [4], [5], [6], [7]). As the production becomes more decentralized, the decentralized response to the electricity demand – known as Demand-Response (DR) – through non-static energy tariff signals emerges to be a valuable instrument to achieve self-stabilizing energy grids (e.g. [8], [9]).

DR has been investigated in various studies and projects for residential buildings (e.g. [6], [10], [11], [12]) and industrial facilities (e.g. [4], [5], [13], [14]). They have shown that DR needs to be supported by automation to yield sustainable results. However, for residential buildings in Switzerland, penetration with building automation systems and a smart meter infrastructure is still low. In contrast, the majority of SSSB are equipped with building automation as well smart meters already today. The analysis of the LSP in the SSSB can therefore be used to gain experience for the LS in the residential building domain. But there is almost no research available about service sector buildings, e.g. office buildings, schools or shopping centres.

Therefore, the research presented in this paper aims at quantifying the potential of DR in SSSB, both from an energy point of view and from a financial perspective. More detailed, we want to quantify the potential of load shifting for the various load groups, and to know how the potential is distributed during the seasons. Then we apply several different tariff signals to this potential, to find out which tariff signal would maximize load shifting benefits, and if a tariff signal that is realizable with the current metering hardware (without smart meters) could already provide major load shifting.

We use existing data sources to calculate LSPs for 10 usage groups, separately for weekdays, Saturdays and Sundays/nights and for each season (summer, spring/fall, and winter). This data we then use to simulate the load shift effect of four different tariff models, and can therefore show their more or less alleviating effect on demand peaks. Using the size distribution of the consumption sites, we quantify roll-out scenarios (smart meters, DR compliant building automation and new tariff models) and their resulting LSP. This allows us also to calculate the possible financial savings by complete load shifting for the different site sizes.

These findings enable DSOs to develop their DR roll-out strategies in a way to prioritize sites with the best effects for a given investment. Moreover, they also allow TSOs and/or DSOs to evaluate their pricing policies and to develop tariff models that promote DR, and thus help them lowering cost for grid balancing energy. This could not be achieved in past experiments with domestic consumers, where it was found that high investments in building automation and smart meter infrastructure yield only small energy cost savings. Therefore up to now DSOs had only little motivation to change tariff models or pricing strategies.

The paper starts by presenting the data sources and outlines the steps how the total technical LSP can be extracted and calculated. In a second part, the temporal behaviour of the relevant potential groups is deduced, in 15-minute time intervals, for each season and for weekdays, Saturdays and Sundays/nights separately. The paper then presents various tariff models in comparison to the currently used one, and selects four representative models for further analysis. They will be used for simulating the LSP, in order to find out for each time interval how much energy is consumed, how much can be shifted and how the shifted consumption is distributed over time. An analysis of the results concludes the paper.

Data & Methodology

A lot of fundamental energy data is collected in [15]. This study focuses on the impact of a smart meter roll-out in Switzerland. iHomeLab goes further and sharpens the image relevant for SSSB by following the deduction of the technical LSP of [15] with several modifications. Therefore we describe the adapted methodology here in detail and refer to the original publication(s) where indicated.

In a first step, we define the total electricity consumption and divide it into groups of devices with similar consumption characteristics, the *potential groups*. In a second step, we calculate the temporal behaviour of the relevant potential groups. This then allows us to calculate for each interval in a year: first, the energy consumption, and second, which portion of the consumption can be shifted and how the shifted energy consumption distributes over time.

Electrical Energy Consumption and Potential Groups

As data source we used [16], [17], and [18], which cover the overall Swiss electricity consumption of the year 2012 broken down to industry, service and business sector. In this research we focus exclusively on the services sector. [16, p. 43] contains a partition along usage groups for the service sector, as shown in Tab. 1, in which 4 TWh/a for agricultural energy usage are also included in the data.

In the services sector, a remarkable high amount is used for drives and processes (27.5%), which also contains cooling processes such as for freezers and coolers. The other most relevant categories are air conditioning (26.6%) and illumination (23.9%).

From an energy point of view a finer partition makes sense. Further, with the premise that neither comfort nor process security are impaired by DR, the following potential groups are suitable for load shifting:

- Specific industry/service processes
- Process heating
- Air conditioning (cooling)

- Ventilation
- Room heating
- Water heaters
- Process cooling
- ICT
- Compressed air
- Pumps for heating

Tab. 1: Partition of the energy consumption (2012) in the Swiss services sector according to usage groups (from [16, p. 43])

Usage groups	Energy consumption [GWh/a]
Total	**17'300**
Drives, processes	4'750
Process heating	640
Air conditioning	4'610
Room heating	940
Water heaters	220
Illumination	4'140
ICT	1'140
Others	860

It is important to clearly distinguish between energy saving measures and time-flexibilisation of energy demand. The latter means load shifting in time with a potential slight increase of energy (without comfort loss) or energy consumption reduction (with a potential cut-back in comfort). The first comprises measures such as switching off unused devices or dimming illumination according to necessity; and only has indirect influence on DR, because it only influences the amount of the (maybe shiftable) consumption.

Out of many proposed DR methods [19], with the premise of no comfort loss, we focus exclusively on load shifting (and not peak-clipping, load curtailing, etc.). It allows making use of electrical energy when it is available in excess and therefore energy prices are low. From a DSO point of view the energy demand can be stimulated by definition of price levels corresponding to energy availability.

To find the realizable LSP – called *technical potential* –, we use the method according to [15], with modifications.

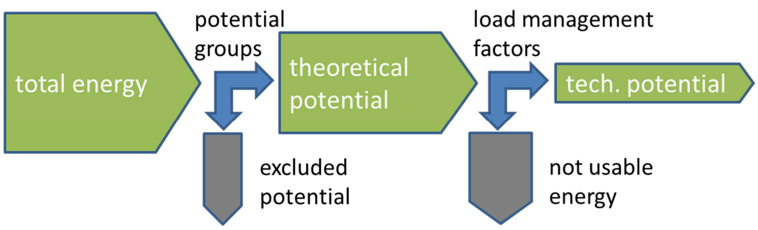


Fig. 1: Method to derive the realizable load shift potential, according to [15]

It applies the following criteria to find groups with load shifting potential:

- The load or consumer has some type of storage. It makes no difference if this storage is a built-in part of the consumer, or if the physical system around the load represents the storage.
- The load or consumer is interruptible or deferrable, and the interruption or deferral only leads to no or only negligible restrictions in the production process.

According to these criteria, we have to detail some of the groups defined by [16], because not all of their applications have the same LSP: “Drives, processes”, “Air conditioning”, and “ICT”. The groups “Illumination” and “Others” have no or a negligible LSP, because lighting is not shiftable without comfort loss. Different to [15], we also omit the LSP for emergency power systems (UPS systems, emergency generators) because we consider them as non-shiftable. In the group “ICT” we can expect a LSP for big data centres, which is not considered by [15]. We then scale the energy consumption data from [15] with the currently available data for 2012 in [16] and assign them to the industry and the services sectors (as defined in [15]). This gives the *theoretical achievable potential* sorted by the different potential groups, shown in the left part of Tab. 2.

Derivation of the Technical Potential

The technical potential is defined as the shiftable part of the total load and the possible shifting duration. The load management factor (LMF) is defined as the percentage of the total load of a potential group that is available as shiftable load. This includes buffering effects and dependencies on business processes (per assumption, we allow no compromises in comfort). Basically, we use the load management factors given in [15], but distinguish between industries and services sector. Main differences are explained as follows:

- A considerable part of process cooling is used to cool food [15, p. 268] and must therefore not be switched off at any time. This leads to a reduction of the LMF from 85% (industries) to 80%.
- The group “Specific industry/service processes” is very heterogeneous. [15] estimates an overall LMF of 10%. We assume that specific processes in the industries are less shiftable than those in the services sector, so we use 5% for industry and 20% for the service sector, respectively.
- Room cooling can be used for DR as long as it is not coupled to some production process (as in a cleanroom or an operating theatre). We assume that for the services sector, a higher percentage is coupled to processes (especially in the medical field) and thus non-shiftable, so we assume 70% instead of 80%.

Tab. 2: Theoretical energy amounts of the potential groups (calculation with modifications from original literature), their LMF and technical potential for industries and services sector (from [15, pp. 270-274], modified).

Potential group	Theoretical potential [GWh/a]	LMF industries [%]	LMF services sector [%]	Technical potential services sector [GWh/a]
Total	**11'390**			**6'070**
Drives, processes				
Process cooling	1'300	85	80	1'040
Compressed air	70	20	75	53
Specific service sector processes	4'160	5	20	832
Process heating	**620**	**15**	**15**	**93**
Air Conditioning				
Room cooling	930	80	70	651
Ventilation	1'870	22	75	1'402
Pumps heating	820	100	100	820
Room heating	**940**	**100**	**100**	**940**
Water heaters	**220**	**25**	**25**	**55**
ICT				
Data centres	460	20	40	184

- We add “ICT” as potential group, because a considerable amount of electricity is used in data centres. In the industry sector, data centres and servers have to be available all the time during production hours, which results in a load management factor of 20%. In the services sector however, reducing the power of a data centre is feasible (it would lead to longer computation times e.g. for a search request), so we assume a load management factor of 40% ([20] anticipates energy savings of 40% - 50% by switching off big data centres if they are not used).
- We do consider neither UPS systems nor emergency generators as shiftable loads. On the one hand, the batteries of UPS systems must always be full, so their charging process cannot be shifted. On the other hand, even if emergency generators are operational at any time, they are not loads, but energy supplies.

Tab. 2 lists the LMFs for both industry and services sectors and the technical potential for the services sector for all potential groups.

Temporal Behaviour of the Potential Groups

In a second step, the temporal behaviour of each potential group is characterized. As the services sector works all year round, most of the potential groups are in use 52 weeks per year. Only groups related to heating are reduced to 39 weeks, and cooling to 6 weeks (according to [15, p. 266]).This is important because the LSP of such a potential group is not available for some weeks in the year, but higher in the remaining weeks. The consumption of the potential groups can also be split up among the seasons. We treat spring and fall the same, and as above only potentials related to heating and cooling are distributed asymmetrical during the year, see Tab. 3.

Tab. 3: Yearly usage and season factors of the potential groups (from [15, p. 266], modified)

Potential group	**Usage [week/a]**	**Season factor [%]**		
		summer	**spring/fall**	**winter**
Drives, processes				
Process cooling	52	30	50	20
Compressed air	52	25	50	25
Specific service sector processes	52	25	50	25
Process heating	52	25	50	25
Air Conditioning				
Room cooling	6	100	0	0
Ventilation	52	25	50	25
Pumps heating	39	0	66	34
Room heating	39	0	40	60
Water heaters	52	25	50	25
ICT				
Data centres	52	25	50	25

Other than [15], we consider only the services sector, so we changed some season factors as follows:

- For room heating, [15] uses 10% for summer, 50% for spring/fall, 40% for winter. Given that in rooms of the services sector, generally more people are present than in the industries, no heating is necessary in summer and less in spring/fall. So we use 0%, 40%, 60%, respectively.

The energy consumption of the services sector also depends on the weekday. Different to [15], we distinguish, as stated above, between industry and services sector and between weekdays, Saturdays and Sundays. Our factors (relative to consumption on a weekday) are listed in Tab. 4. The factors include energy saving measures such as switching off some devices during weekends (because then these loads are not available for shifting). We assume that in the services sector, activity on Saturdays is 80% compared to weekdays, on Sundays 20%.

For the most part process cooling is used to cool food [15, p. 268] and must therefore not be switched off during weekends. For process heat this is different: we assume that due to energy savings measures, HVAC (heating, ventilation, air conditioning) is reduced while no personnel is on the premises. Big data centres also are not as busy on weekends as on a weekday. Based on these considerations, we use the numbers in Tab. 4 as weekday factors.

Tab. 4: Day/night factors of the services sector potential groups (from [15, p. 268], adapted)

Potential group	**Day/night factor [%]**		
	Weekday	**Saturday**	**Sunday / night**
Drives, processes			
Process cooling	100	100	100
Compressed air	100	80	20
Specific service sector processes	100	80	20
Process heating	100	80	20
Air Conditioning			
Room cooling	100	80	20
Ventilation	100	86	30
Pumps heating	100	100	20
Room heating	100	95	75
Water heaters	100	80	20
ICT			
Data centres	100	95	75

For a complete temporal load model we need also to distinguish between day and night. As proposed in [15], we divide the 24h-day in two parts, day and night of 12 hours each. During the night, we assume the same factors as for a Sunday. While the 12-hour-day is realistic (or even too short) for shops or leisure facilities, offices usually have shorter hours. By using 12 h nevertheless, we compensate shift-work and unusual work schedules.

Further details about LSP realisation are left open at this point. We assume that DR will replace direct load control used today, in order to get a complete picture. Therefore, we do not introduce a reduction factor for direct load control in contrast to [15, p. 277].

With the time shift model available on the one hand and the load management factors (and thus the technical potential) on the other hand, we still are missing a piece of information to be able to simulate load shift: We need a model about the possible duration of the delay and the necessary pre-announcement time.

This shifting potential vs. time according [15] is shown in Fig. 2. In addition to the pre-announcement interval t_{pre}, the curve contains a „minimal time“ t_{min}, which is the interval during which the load can be shifted without loss of comfort, and a “maximal time” t_{max}, which gives the longest possible shifting interval (i.e. after this time, the load must be supplied with energy again). The case without pre-announcement can be treated the same, with an announcement time t_{pre} of zero. For simplicity we only shift loads to a later point in time, never to an earlier one in our calculations. As we will look at the total SSSB energy sum over the whole year or season, this makes no difference in the compound figures. Therefore in this paper we do not take into account the well-known “rebound effect”.

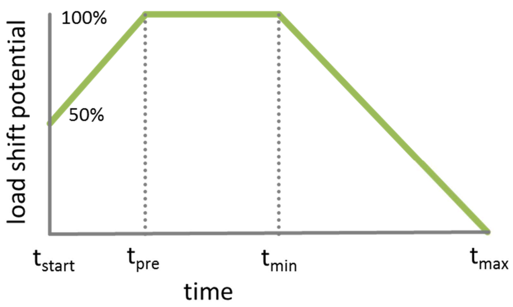


Fig. 2: Model for the potential of the load shift times, with pre-announcement

The pre-announcement times t_{pre} have been evaluated in detail by [15] and are used in this paper with some adjustments:

- No specific reference values can be found for data centres, so we have estimated them using [20]. As shifting the load means only a reduction of computing power, it can be done during a longer period.
- For heating pumps we have reduced the numbers of [15] by 50%, because such pumps need to manage the thermal reservoir partly also when the heating is not used.

The resulting values are listed in Tab. 5.

Tab. 5: Adapted load shift times (after [15, p. 276])

Potential group	**Minimal time [minutes]**	**Maximal time [minutes]**	**Pre-announce-ment time [minutes]**
Drives, processes			
Process cooling	60	240	0
Compressed air	0	30	0
Specific service sector processes	30	180	30
Process heating	30	180	30
Air Conditioning			
Room cooling	15	60	0
Ventilation	15	60	0
Pumps heating	120	240	0
Room heating	240	480	0
Water heaters	60	180	0
ICT			
Data centres	60	120	15

[15] suggests prolonging these intervals during weekends and nights, because reduced personnel on site means less energy consumption (e.g. for ventilation). Therefore we added the following intervals to the minimal time and the maximal time (cumulative):

- plus 30 minutes during the night from Monday to Friday
- plus 30 minutes during the day on Sunday
- plus 30 minutes during the night on Saturday and Sunday

Now we can calculate for each point in time and per potential group: (1) the amount of electrical energy consumption and (2) how much of this can be shifted given a trigger and how the energy is shifted over time. Examples of these calculations are given in the results section.

Applying Tariff Signals

The DR-approach we have chosen for our project is to control one building (or several buildings on one site, if the building control system is set up that way). This basic DR cell makes sense in a way that in the service sector this partitioning is also usually the economic basic cell. The building or site reacts autonomously on a given tariff signal in order to minimize its energy costs. In this paper, we list existing and possible tariff signals, categorize them and then select four representative ones for further investigation.

The various tariff models for DR found in literature (see overview in [1]) can be divided into two main groups: incentive based and price based programs. For our project, we only examined price based ones.

TSO and DSO want to encourage energy consumption when there is plenty of supply (e.g. from renewable sources as wind or solar radiation) and energy savings during times when less energy is produced. This situation is already reflected in the electricity wholesale price, so one of the logical tariff models is to charge the end-customer fluctuating prices reflecting the real cost of electricity in the wholesale market. This is called *real-time pricing (RTP)*. Because the wholesale prices are defined on the day ahead, also the RTP price signal can be announced on a day-ahead or hour-ahead basis. In this regard, it is important to note that RTP is not the same as prices from a real-time energy exchange, where energy prices are negotiated on short notice between the participants of the energy stock exchange. In order to boost the load shifting effect, the tariff signal could be modulated to amplify fluctuations, as described e.g. in [21]. We include a tariff signal with quadratic coupling to the load profile after [22] and call it *RTP+*. Such a signal also reflects higher costs for load peaks due to generating power restrictions

The price signal that is used nowadays in most parts of Switzerland assumes that there is excess energy during the night, so the tariff system depends on the time of day of energy usage, with a lower nightly tariff. Such tariff systems are called *time of use (TOU)*. They could involve more levels (6 have been tested in [23]), different tariffs according to season, weekdays etc. To be able to estimate the effect of DR in the current tariff situation in Switzerland, we include into our simulations a simple TOU model with 2 levels, independent of the season and with same times on Monday to Saturday (Sunday on lower level).

TOU models as the above do not stimulate load-shifting according to a variable energy production, because there is no short-term variability in the tariff. *Critical peak pricing (CPP)* includes such an element. It is based on a flat or TOU tariff model and adds a peak tariff that is valid only for short periods of time (e.g. between 15 min. and 2 hours) and announced on relatively short notice (e.g. the day before). However, the price for the peak tariff and its maximal duration and frequency are fixed and communicated in the contract. Such a tariff model is only moderately complex to implement (most of the existing infrastructure in Switzerland can already handle three price levels), but allow the DSO to give incentives for load-shifting. We include into our simulations a CPP tariff based on a two-level seasonal TOU tariff and call this tariff model CPP+.

The four tariff models we use for simulations represent a good selection from the wide variety of tariff models: 1) TOU, which is a simple and widespread tariff, 2a) and 2b) as two versions of RTP, which are at the opposite end of the complexity scale (one with linear, one with quadratic coupling to the price signal), and 3) a CPP based on a two-level tariff, which represents a compromise between technical simplicity and flexibility for incentives.

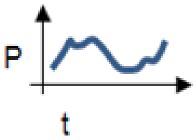
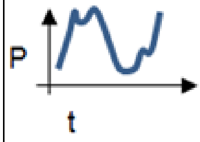
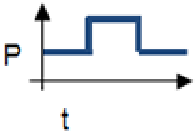
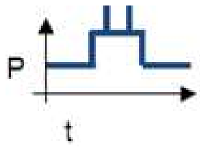
To be able to compare the results, we have designed the detailed prices for each tariff model such that the total energy cost – for end users and DSO – is kept constant compared to the initial situation with no load shifting, using standard load profiles. Additionally, we assumed the following:

- Possible price changes because of changed user behaviour with modified energy demand due to DR are not fed back into the models.
- No differentiation is made between grid cost and energy cost, we use a weighted overall sum.
- An average energy price of 14.41 Rp/kWh is derived from the 2013 Elcom data [24], with mapping the industry and service sector tariff user groups C1-C7 to the total energy consumption of each user category as described in [15, p. 124].

- Energy shifting is considered as free, the cost of additional arising energy storage is neglected.

The resulting tariff models and their detailed parameters can be found in Tab. 6

Tab. 6: Cost neutral price models for DR

RTP[a] 	**Real Time Pricing** • Variable tariff signal with linear coupling • Complexity high • Incentive low	RPT+[b] 	**RTP spread** • Variable tariff signal with quadratic coupling • Complexity high • Incentive medium
TOU[c] 	**Time of Use** • Double tariff with long term stability • Complexity low • Incentive low	CPP+[d] 	**Critical Peak Pricing** • Variable double tariff with two critical peaks • Complexity medium • Incentive high

[a] Load profiles according to [22]
[b] Based on RTP and quadratic coupling
[c] Low tariff (LT) 9.75 Rp/kWh, high tariff (HT) 17,72 Rp/kWh
[d] Peak duration winter 2 h, summer 1.5 h, tariff spread factor: 1.5 x HT
Winter: LT 9.75 Rp/kWh, HT 17.72 Rp/kWh, Peak 26.80 Rp/kWh
Transient: LT 8.84 Rp/kWh, HT 16.08 Rp/kWh, Peak 24.12 Rp/kWh
Summer: LT 7.86 Rp/kWh, HT 14.90 Rp/kWh, Peak 21.44 Rp/kWh

With these four tariff models we have calculated the achievable energy cost savings in the service sector, based on the LSP presented in section “Load Shift Potential”. A promising tariff candidate with moderate communication and infrastructure requirements is the Critical Peak Pricing (CPP) based on a Time Of Use (TOU) double tariff with two critical peaks per day, called CPP+. Price levels usually vary per season. For our initial calculations, we assumed a moderate critical peak price of only 1.5 x the price of the higher TOU tariff level. In literature, spreads up to a factor 10 are reported ([13], [25], [26]), to gain relevant load shift incentives.

Results

Roll-out Scenarios

As a first result, we can use the data of [15] regrouped according to the size of the sites and derive roll-out scenarios. The total electrical energy consumption of the service sector in Switzerland in 2012 is 16 TWh ([16], [17] and [27]) – about the same amount as in the industrial sector. The number of sites within defined ranges of energy consumption can be derived from [12]. The distribution of the cumulated annual energy consumption vs. the cumulated number of service sector sites is shown in Fig. 3. Under the assumption that the LSP is proportional to the energy consumption of a site, this data shows that 50% of the total load shift potential (LSP) can already be realized by addressing only 1.7% of all service sector sites.

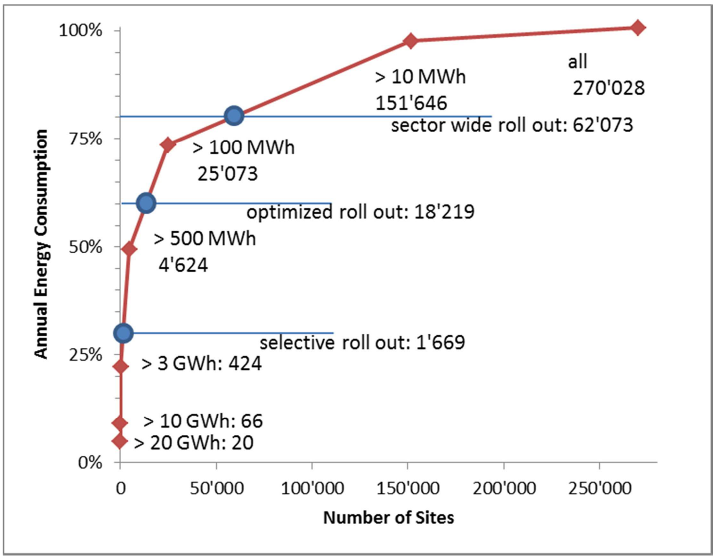


Fig. 3: Cumulated energy consumption vs. consumption size categories

Based on this, we consider three potential roll-out scenarios for DR until 2035. This timespan matches the currently discussed energy perspectives ([28]) of Switzerland. For each roll-out scenario, we propose how many buildings of which electricity consumption level have to be equipped with DR infrastructure. As shown in Tab. 7, the DR LSP could be realized to a remarkable share of 65% if only 7% of all service sector sites are included (scenario "Optimized").

Tab. 7: Roll-out scenarios

	Selective	Optimized	Sector Wide
Realized LSP	1.8 TWh/a 30 %[a]	4.0 TWh/ a 65 %[a]	4.9 TWh/a 80 %[a]
Number of Sites	1’669 0.6 %[b]	18’219 7 %[b]	62’073 23 %[b]

[a] of full LSP of 6.1 TWh/a
[b] of all 270’028 utilities (SSSB)

Load Shift Potential

The simulation of the LSP – according to the methodology described above – for all usage groups, separated for weekdays/Saturdays/Sundays and for each season, leads to the results in Fig. 4. It shows the profiles of the LSP power vs. the possible shift duration, for an average weekday, Saturday and Sunday in each season (the Sunday profiles are also valid for nights).

We observe significant seasonal and intraweek differences of the technical LSP. In summer the technical LSP power peak (dominated by air conditioning), is 45% higher than in winter, but available only for 15 to 60 minutes. Note that cooling is calculated only for 6 weeks in summer, so the LSP of a midsummer day shows a high peak, which is not available for all 13 summer weeks. In winter the LSP is dominated by room heating loads. Therefore a time shift in the range of several hours is feasible, but with a lower power level.

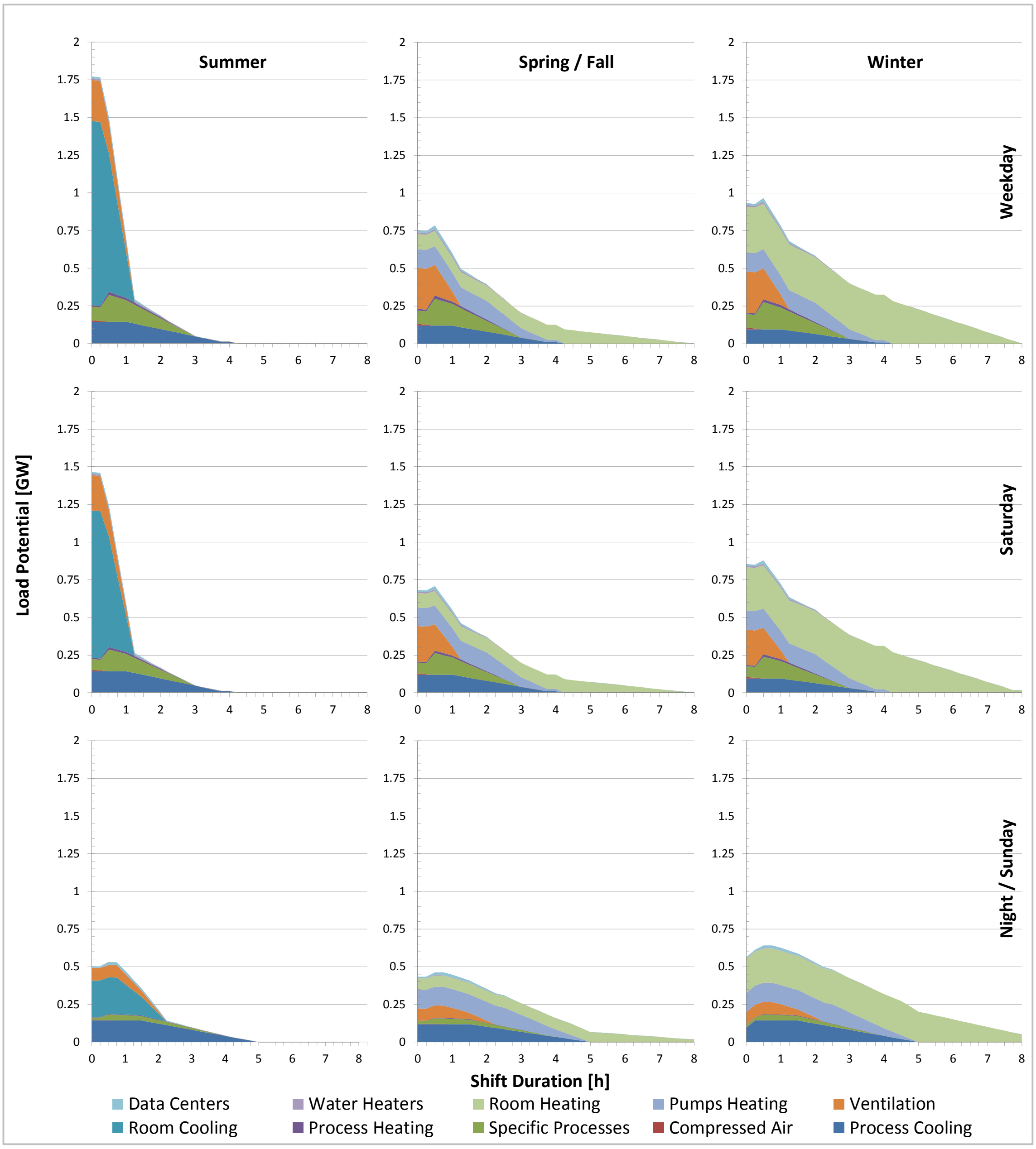


Fig. 4: Achievable load shift potential, split into usage groups, for a typical day of each season and weekday category. Sunday profiles are also valid for nights.

Effect of DR on Peak Consumption

To assess the economic viability of the DR we calculated the user benefit for the four tariff models described in the previous section. First we applied a specific tariff signal to the LSP and calculated the resulting energy cost. Then we shifted the energy consumption within the limitations given by the LSP curves, starting at the beginning of the peak pricing period, and applied the tariff model to the new LSP profile. The cost difference between initial energy cost and load shifted energy cost is defined as load shift profit.

We used the prices as listed in Tab. 6 and its footnotes, and made the following assumptions:

- Total load profiles are taken from [22] for summer and winter season. For spring and fall, no separate data is available, therefore we used the average of summer and winter profiles.
- Time resolution of the data is 15 minutes.

As an example, the peak flattening and broadening effect by using DR driven load shifting is shown in Fig. 5 for a CPP+ tariff model with a price spread of factor 1.5 and the roll-out scenario “Optimized”.

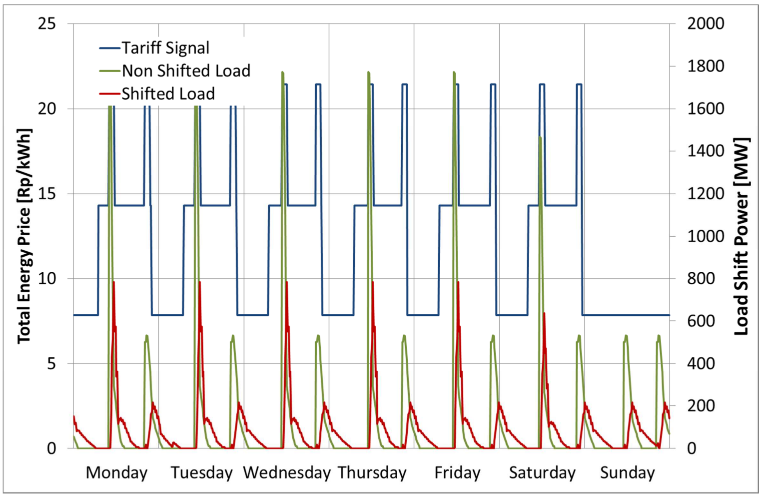


Fig. 5: Sample load, non-shifted and fully off-peak shifted. Responding to CPP+ tariff, for optimized roll-out scenario in summer time

Financial Load Shift Benefit

For the different size categories of utility sites, we calculated the expected financial benefit of load-shifting for each proposed tariff model per site. The results are displayed in Fig. 6 and show that especially sites with high energy consumption can profit from DR substantially, but for all site sizes, CPP+ results in the highest financial load shifting benefit.

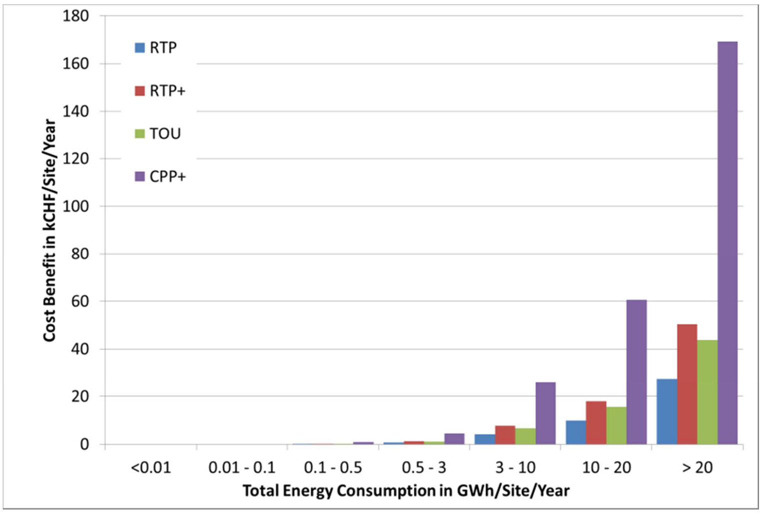


Fig. 6: Cost benefit per site and year for different total annual energy consumption categories per site with the optimized roll-out scenario

Discussion

In this paper iHomeLab has deduced the LSP for SSSB from existing energy consumption data. Our calculations show that the LSP for the service sector is higher than the one for the industry sector, with 20% of the energy consumption compared to 13%, given that the compound annual electrical energy consumption is of the same order for both sectors. The reason can be found in the fact that the services sector has less non-shiftable energy-intensive processes. Further we have shown that the distribution of site sizes and their associated LSP allow a highly cost-effective roll-out scenario. The Pareto principle is valid here too – i.e. targeting the biggest site sizes only, a prominent portion of energy consumption can be shifted already. The fact that most big sites nowadays are already equipped with the necessary building control systems and smart meter infrastructure again increases the financial benefit.

Modelling in more detail the LSP, we derived that it varies significantly per season, weekday and time of day. As expected, thermal loads offer the biggest potential for load shifting. In summer, these are ventilation and air conditioning, while in winter, it is the room-heating. Based on the load-shift characteristics of the relevant supplies, the total shift duration is much longer in winter than in summer. Moreover, smart load shifting distinctly flattens consumption peaks. This leads to more stability in the overall grid, and therefore also less necessity for grid expansion and upgrading. These findings are important for the residential sector too, because there, similar thermal loads are in use, like room and water heating and cooling. Moreover, the method of calculating the LSP for weekdays and seasons can be applied to the residential sector too, once the necessary fine-grained statistical energy usage data is available.

Providers of electricity and electrical energy services currently have a top-down approach to deal with peaks (direct load control or pooling). Our approach is bottom-up, based on sites, with price-induced load-shifting, and thus does not rely on enforcement, but on cost benefits. This will change the energy landscape, but of course, the pricing still lies within the power of the DSO and TSO.

Looking back critically to our research presented in this paper, we have made some assumptions, stated explicitly in the text above. These assumptions on the one hand limit the generality of the results, on the other hand lead to representative quantitative findings and also open the door for succeeding research work. We have used some LMF and arrangements of the potential groups different than those in literature (see “Data & Methodology”) because, to the best of our knowledge, no studies are available yet that target specifically our field of research, the Swiss service sector. To derive data for the services sector for 2012, several statistical sources were combined carefully. With a look at [16], our data is consistent. We have assumed that the mix of potential groups is homogenous among sites of different sizes. Of course, this is true for statements about the total summed electricity consumption in SSSB of Switzerland. If the focus is set to a specific single building, the actual mix of the available potential groups has to be taken into account and applied for LSP calculation. For the calculations we assumed the reduction of the weekday energy consumption to 80% on Saturdays, respectively 20% on Sundays. This has to be proven by additional specific research or studies. For financial benefit calculation we defined several specific tariff models: we parametrized the tariff models such that the total non-shifted energy consumption cost is cost-neutral. Even with this very conservative approach and small tariff spreading, remarkable effects were shown. Sensitivity analysis of tariff parametrization can be carried out in further research. Also, local production and storage has been considered for the total service sector in sum and not for a single building. For increasing directly energy autonomy of a single building, this can be studied separately in further research, as indicated in last phase research of [13] in order to flatten local grid bottlenecks.

In experiments with real-time energy market and real-time energy tariff models, oscillation effects of loads and tariffs have been reported (e.g. [29]). Although our approach uses a pre-defined price signal and does not include such short-time price adaptations, a feedback to the DSO about the expected energy consumption is foreseen. It has to be proven in practice that this coupling effect does neither prevent the proposed DR model from flattening the peaks nor lead merely to a peak shifting.

With the TOU or flat tariffs currently in effect, building control systems optimize costs by minimizing energy consumption, by switching loads “as late as possible” before effective use. With the results of our research, these systems can react to variable tariffs and still optimize costs. This will not minimize energy consumption, but rather shifts the electricity consumption towards times with high availability – without compromising comfort. Thus, it facilitates balancing energy consumption with the production.

DSOs in turn need to develop new tariff models helping them to flatten load peaks and to stabilize the grid effectively. This entails new products for balancing energy. The WARMup project [30], which does research in this field and pools local storage, is still running and might yield interesting results. However, it still uses a top-down approach and targets the currently available products for balancing energy. We consider the current definition (where balancing energy must be available at all times) as too rigid for SSSB and residential buildings with local renewable production and storage. New products must be more flexible in order to stimulate the switch from “production follows consumption” to “consumption follows production” actively. This is also a chance for a new allocation of roles in the energy landscape, by including renewable energies, while conserving the energy producers’ flexibility to guarantee the energy supply stability.

In the SSSB, with few installations a lot of experience can be gained. In the residential sector the market currently is bustling with several big companies boosting home automation (Google Nest, Apple HomeKit, and Samsung SmartHome). Moreover, data communication will be facilitated in near future by the glass fibre network roll-out pushed all over Switzerland also by the DSOs. Our research represents a remarkable contribution to this very active field of “smart homes” and consumer building control systems, and our results and methods presented in this paper can be transferred to the residential sector for the upcoming introduction of DR.

Acknowledgments

Without the expert knowledge and financial support of our partners from BFE, BKW, MeteoSchweiz, Siemens and Swissgrid, this work could not have been realized. These partners represent a complete set of stakeholders in the field of DR and therefore give iHomeLab a unique chance to study the LSP of SSSBs in Switzerland in depth.

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How to improve households' participation in Demand Response programs: the promising contribution of predictive control

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Abstract

An increasing attention has been paid to Residential Demand Response programs from utilities and aggregators of dispersed capacities have emerged looking for demand response (DR) products which can be characterized in terms of power reduction and time duration. With the incoming results from some of the numerous smart grid demonstrators, it has been observed that households might not respond to price signals or at least not as much as expected. For programs aiming to reduce peak demand, the choice of the control strategy is the key issue for increasing households' involvement. For electrical space heating, in order to be fully efficient, the control strategy should depend on the building's characteristics and take into consideration household's behavior or habits.

If the control strategy implemented uses only standard bound limits for indoor temperature as the comfort constraint, households facing discomfort situations might withdraw from DR programs or stop responding to it. This case is more likely to occur for low mass envelope buildings which represent the largest part of the French building stock and which have the highest load curtailment potential in terms of power demand. We suggest to compare different control strategies to evaluate the potential for load curtailment under comfort constraints for several types of buildings (those buildings have different level of insulation) modeled using a simplified thermal model for building and different types of electrical heating systems. Using a day as the time horizon and considering that the maximum peak period is two hours, we identified four control strategies as suitable for load curtailment programs, including a predictive controller with comfort constraints.

The strategies are compared for each type of building in terms of load curtailment potential (characterized by power and duration of the curtailment) and consumed energy during the day. We also compare them accordingly to the discomfort indicators we defined.

While those strategies lead to comparable results for well insulated buildings, the more sophisticated strategies can be interesting for poorly insulated buildings as they allow a diminution of discomfort effects and an increase in households' participation and interest in DR programs.

Introduction

Some challenges and barriers for direct load control management of space-heating systems

If we look back at past smart grids experiments aiming to assess the potential for load curtailment, it can be noticed that, even if drawing general and definitive conclusions about households' commitment to the projects is not obvious; the level of participation is not as high as expected and the estimated achieved load curtailment potential is not as important as forecasted.

First of all, sociological studies about households' energy consumption have shown that the levels of consumption are very heterogeneous. This observation is valid either when the population set studied is at national level [29] or at a local level [3] (for example studies conducted over a set of consumers receiving the same signal from a demand side management program). In addition, the information they have about their own electricity consumption is incomplete and biased by their own beliefs [30] More recently, sociological models have been suggested, such as the Consumer Lifestyle Approach [5], showing out the importance given to behavior in electrical consumption

From economic studies on demand response programs, we can observe that finally the estimated price elasticity varies significantly when considering either TOU rates of dynamic pricing [13]. One of the identified issues which could explain these results is the price unresponsiveness of the households. For example, in the study conducted by Reiss and al. [26], the authors concluded that there are two main categories of households: those who use HVAC and/or electrical space heating and who showed some response to the program and the others. But even in the first group, the rate of response found was small compared to the evaluated potential or the expected level. One side of the problem might be the lack of availability of households to look each day and hour for demand response signals and control their electric heating and devices. One might also assume that the economic or price signal is not well adapted to households' diversity.

Back in the early 90’s, studies about thermostat set point showed also an important disparity among households. Nevertheless, more recently, it has been showed [35] that in the USA, one given household use limited thermostat set points: 2 are frequently used, 3 less often. Similar observations are emerging from the observation of the data collected in the residential energy consumption survey from 2009 [31].This means that households might have a temperature preference, even if this preference is not only related to their behavior but also includes observations they might have acquired from the knowledge of their dwelling, systems, outdoor climate, or any other factor. However [23] stressed out the difficulty for households to understand how to use properly a thermostat.

Finally these studies have demonstrated that consumers considered as individuals do act neither in a rational manner nor in a uniform and standardized manner. This absence of full rationality and the heterogeneity in households’ energy behavior helps to grasp the challenge to determine signals able to achieve the full potential of load curtailment by households. We suggest also that for some buildings, it is not satisfactory for the households to use a simple on/off switch for direct load control because the household characteristics does not allow curtailing as much power as in the most recent buildings.

On the basis of these lessons from the field, our claim for the coming sections is that advanced controllers for heating devices may help to overpass these barriers, as some of them allow a remote and adapted control of devices which is one of the first technical prerequisites to achieve the full potential of load curtailment by households. But in the other hand this remote control may strongly interfere with local comfort conditions which may lead to households’ withdrawal from DR programs.

In this paper, we evaluate the ability of an advanced heating controller, the Model Predictive Controllers (MPC), to handle varying energy price signals under comfort constraints in order to assess the potential of load flexibility of residential consumers.

Challenges about (dis)comfort indicators

The implementation of comfort (or discomfort) considerations into regulators needs to define what we mean by comfort. First, one should keep in mind that the notion of comfort only exists because people are facing discomfort situations. For residential space heating and direct load control, this means that whenever a household is in a discomfort situation during a curtailment, it might be attributed directly to the aggregator and a repetition of this situation might lead to a withdrawal of the dwelling from the program.

Thermal discomfort situations are closely linked to the thermal sensation perception which is a complex notion. Building thermal performance studies generally use the Predictive Mean Vote (PMV) as the comfort indicator. The notions of PMV and PPD (Predicted Percentage of Dissatisfied) have been proposed in the 70’s by Fanger [12] and those indexes have been used by the ASHRAE as standardized comfort indicator [4] and also in European norms [1].

Another indicator widely used to estimate comfort is the “comfort index”, a global indicator which is based on three factors to asses comfort in buildings: the thermal comfort – evaluated with the PMV index, the visual comfort and the indoor air quality (IAQ). Visual comfort is linked to luminance while indoor air quality is generally evaluated through the estimation of the CO2 concentration in the building. The last two indexes mentioned are beyond the scope of this study since we are only interested in thermal comfort and we do not have access to measurements of luminance or CO2 concentration, but energy management programs based on this indicator have been proposed [36], [2].

One major criticism formulated on the PMV is that it is a stationary index, meaning that humans are considered not to interact with the building and systems while field observations have shown that households do interact with heating systems and/or the building [19], for instance by adjusting the set point or opening the windows. Adaptive models have also been proposed [9] dealing with thermal comfort in office buildings during the summer for naturally ventilated and HVAC equipped buildings [10]. As for winter periods, other models have been suggested leading for example to the EN15251 standard. Leen and al. [221] have suggested an adaptive thermal comfort guideline distinguishing 3 types of rooms, and for each, giving acceptable temperature range depending only on the exterior temperature. Taleghani and al. [32] compared those methods for a city and observed similar results with all the methods.

These indexes are useful for energy performance calculations prior to the building construction, but they may not be applicable for thermal comfort estimation during use of the building. This is why, in order to model properly dynamic discomfort situations as well as evaluating energy behavior of heating devices, we developed a detailed thermal model and we define the conditions of the experiments. We propose two models for the heating controller (PI and MPC) and for each, we suggest two control strategies based on sent signal interpretation. Then we define meaningful indicators to evaluate the performance of the strategies in terms of energy consumption and comfort criteria.

Building model used

Description of the building model

In this section, we briefly describe the model we built to simulate the thermal response of a single zone building. Based on [33], we developed a high order building model using a discrete 1D scheme to discretize each layer of each wall. The air inside a zone is represented by a single thermal node. This model takes into account the following heat exchanges:

- Conduction through walls
- Convection at the air layer interface
- Long-wave radiation originating inside the building and from external sources
- Short-wave radiation coming from external sources

There are two types of inputs:

- the controllable inputs, noted U. In our case, the only controllable input is the heating power
- the non-controllable loads, noted W. In our model, we considered that $W = [I_{\text{dir}}, I_{\text{diff}}, T_{\text{ext}}]'$

Additional inputs such as internal gains could have been added but as we lack information about their values on-site in operational situation, we set them to 0. We end up with a state-space model where the states are the temperatures in the building:

$$\begin{cases} \overset{\circ}{T} = AT + B_1U + B_2W \\ Y = CT + D_1U + D_2W \end{cases} \tag{0.1}$$

This model can be reduced using techniques such as Moore's balanced realization [24], or Hankel-optimal norm techniques [17], [11], to a model of very low order (2 or 3). This reduction is crucial in our study case since we need a model as simple as possible to reduce computation time, but as accurate as possible for the calculation of the optimal trajectory with the predictive controller. We used Moore's method to reduce the system to the order 5, which is very satisfactory as we will see in the following sections. This new low order model is referred with the same name as the full model of equation (0.1) to limit the number of notations used.

Once the model has been reduced, we use a zero order hold for the simulations to build an equivalent discrete system, using the time step Δt_0:

$$\begin{cases} T_{k+1} = A_d T_k + B_{d,1} U_k + B_{d,2} W_k \\ Y_k = C_d T_k + D_{d,1} U_k + D_{d,2} W_k \end{cases} \tag{0.2}$$

Description of the building parameters

General building description

We consider the case of a detached and single storey house building of 80 square meters located in Trappes, France. The size of the house is representative of the mean size of French houses built over the last 20 years. We assume that the windows' area represents 15% of the living area which is also representative of the mean value in France over the last decades. Half of the windows are located on the south façade while the 50 remaining percent are on the north one. Each wall is composed of several layers, the thickness and thermal properties of those layers depend on the construction period of the house (see next section).

Building study cases

The French building stock falls into several categories depending on the construction period. We suggest to compare the strategies on houses representative of 3 typical construction periods and we consider the same house, described above for each class. Table 1 gives some magnitude orders for energy consumption. We use different materials for the layers with different levels of thickness. For a class, we consider high level of insulation as well as low insulation level (in the high insulation level, the lagging material is on the outside layer while in the low level it is the inside layer which is the lagging material).

Table 1: Typical energy consumption for the building cases studied

Type	Period of construction	Type of house insulation	Annual energy consumption range	Typical wall construction
RT88	1988 - 2004	Low insulation	213-330 $kWh_{pe}/m^2.year$	0.2 m of concrete 0.05 m of insulation
RT05	2005-2011	Medium insulation	91-150 $kWh_{pe}/m^2.year$	0.2 m of concrete 0.12 m of insulation
RT12	Since 2012	High insulation	<50 $kWh_{pe}/m^2.year$	0.2 m of concrete 0.26 m of insulation

Description of the external conditions

Weather data

As mentioned, we only consider here the case of a single detached house based in Trappes, France. We used weather data from meteonorm [20]. In order to evaluate the incident solar flux on the house based on the data from meteonorm, we used the method developed in [16].

Reference scenario

We consider a simulation period of five working days. We assume that households use the same two controller set points each day: X °C between Y and Z hours and A °C between B and C hours. In order to evaluate the flexibility of the power demand, we consider several reference scenarios depending on the moment where the set point is changed from $T_{sp} - 2$ to T_{sp} at night. We consider the following hours: at the beginning of the load curtailment period, 30 minutes after the beginning of the curtailment period and at the end of the curtailment period as reported in figure 1.

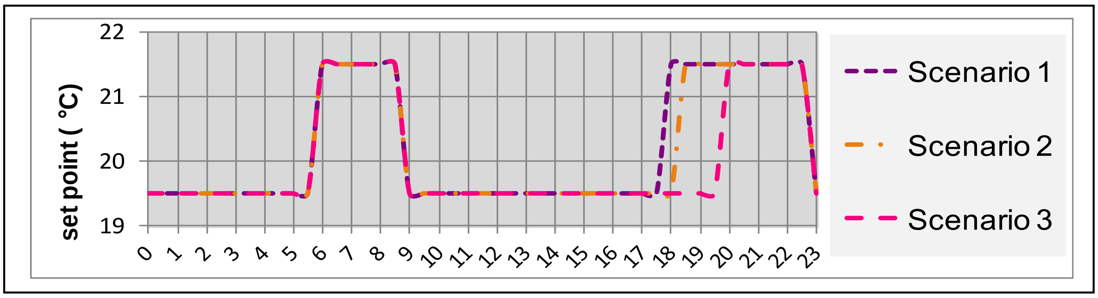

Figure 1: Typical working day scenario, with 2 set points

Control strategies

We consider four control strategies, two of simple ones (S1 and S2) and two are based on model predictive control (S3 and S4).

Current strategies for load curtailment based on direct control

The first control strategy considered, *S1,* consists in cutting the heating power off when a price signal is sent to the households. The power is cut off during the entire period when the electricity price is high.
In the second strategy, *S2* is similar to *S1* but instead of simply cutting the power off, the temperature set point of the thermostats is set to the comfort value T_{sp} one hour prior to the peak period. For those strategies, since the heating systems are disabled during the load curtailment, changing the set point during the curtailment will not have any effect on the load curve. Thus, the second strategy consists in changing the set point one hour prior to the curtailment. As a result, the comfort will be improved but the control strategy performance will be degraded (regarding the energy consumption). For These strategies, the temperature regulator is the one available in the heating system and is supposed to be a PI type (PI: Proportional & Integral regulator).

Implementation of advanced control strategies based on model predictive control

In order to improve the strategies for the sake of comfort, we suggest replacing the system regulator with an MPC. In general, the internal regulator of the heating system is still available in the control loop to avoid having an open loop system between two predictions of the MPC but as our study is based on simulations, we can handle the disturbances without the internal regulator. The controller can communicate with the aggregator (upper level), and receives estimations about the weather as well as a signal about future electricity prices. In order to use a predictive controller, we need to identify a model for the building system (estimator). In our case study, we assume we are in the best case scenario, meaning that we use the building model directly as the estimator. Then, the predictive controller will give lower performance if implemented in a real building.

Model Predictive Controllers have been widely used for a variety of industrial processes, including applications to building thermal control [27]. As for building application, an interesting feature about MPC is its ability to deal with constraints on input and output signals, even with MIMO systems (multiple inputs/multiple outputs). A detailed overview of MPC applications for building thermal control can be found for example in [21].

A predictive controller calculates the optimal command signal for a future horizon H_o knowing an estimation of future non-controllable signals, based on the minimization of cost function objective, under constraints on inputs and/or output signals. This cost function can be expressed in the general form [34], [25]:

$$J = \frac{1}{2}\min_{\{u,y\}} \sum_{k=0}^{N-1} \left[\| y_{k+1} - T_{sp,k+1} \|_{l,Q} + \| \Delta u_k \|_{l,R} \right] \tag{0.3}$$

The choice of the norms ($l = 1$ or $l = 2$) in the cost function will lead to linear (LP) or quadratic (QP) programming problems, the latter one having the largest computational cost. In this study, our goals are to maximize the comfort, meaning minimizing the gap between the room temperature and temperature set point, and to minimize the energy consumed by the space heating systems, meaning we want to minimize the command signal$\| u_k \|_{l,R}$. One should notice that since the only heating systems considered are electrical convectors, the increment can be large, and the control signal is only bounded by the maximum available heating power. As a result, we write the objective function in the following form:

$$J = \frac{1}{2}\min_{\{u,y\}} \sum_{k=0}^{N-1} \left[(1-\alpha_k) \| y_{k+1} - T_{sp,k+1} \|_{2,Q}^{2} + \alpha_k \| u_k \|_{2,R}^{2} \right] \tag{0.4}$$

Where α_k is a tradeoff parameter between the two objective functions, R and Q relate to the fact that the norms can be weighted. We will discuss about those parameters.

Input and output signal constraints

Generally, the following constraints can be added for the minimization process:

$$\begin{cases} u_{\min,k} \le u_k \le u_{\max,k} \\ \Delta u_{\min,k} \le \Delta u_k \le \Delta u_{\max,k} \\ T_{\min,k+1} \le y_{k+1} \le T_{\max,k+1} \end{cases} \tag{0.5}$$

With the sampling time $t_k = k\Delta t$, $0 \le k\Delta t \le H_o = (N-1)\Delta t$. If necessary, the lower and upper bounds can be adjusted over time. The constraint on the input signal (power supplied) allows to bound the power between 0 (system off) and the nominal power of the system $P_{\max}$. The constraint on Δu_k is not useful in the specific case of electrical convectors, thus we disregard it. The constraints on the output signal, which is the room temperature, represent comfort constraints. One can notice that since the distance to the set point is part of the objective function, the bounds on the output are unnecessary but they are used as comfort constraints as soon as one consider the specific case $\alpha_k = 0,\ \ k \in [\![0; N-1]\!]$.

For instance, when the focus is on the consumed energy, authors have used output constraints to assess thermal comfort [14], [6] while using the consumed energy as the cost function. If so, the resulting optimal command will maintain the temperature as close to the lower bound as possible: the lower bound should be chosen equal to the temperature set point. As mentioned previously, characterizing the thermal comfort using only an absolute value of temperature may lead to an unsatisfactory regulation as thermal comfort is not a static but a dynamic notion. Therefore, as humans might rather feel changes in the temperature, we consider constraints not only in the output signal but also on its variation ΔY_k .

In [15], the authors develop and implement a MPC, with a quadratic formulation, to control the heating system of a university building, which consists in a ceiling radiant system connected to an urban heating network. The output signal of the system is the temperature of the hot water supplied and a constraint on the temperature variation between the hot and cold water was added.

In [7], the author proposed an algorithm to minimize the energy consumption in a building using dynamic programming (using Bellman principle) under comfort constraint. He used ASHRAE standard 55 to express constraints on: the operative temperature, the maximum rate of change in the operative temperature during temperature rises and the maximum peak-to-peak amplitude of the temperature fluctuation. Then he computes the optimal set-point and optimal heat supply power given by its constrained cost function.

Similarly, we suggest to impose a maximum rate of change for temperature drops in order to control the temperature falls during load curtailment periods:

$$\frac{dT}{dt} \ge -1°\mathrm{C}\cdot\mathrm{h}^{-1} \text{ if } \frac{dT}{dt} \le 0 \tag{0.6}$$

This constraint might be always satisfied for recent buildings but for the older ones, the thermal inertia might be inadequate to handle the intermittence generated by the price signal.

Optimization problem formulation

With constraints on both input and output signals, the optimization algorithm may not converge. One way to deal with this is to relax the constraints either on the input or output signals. As it is generally not possible to do so on the input constraints, the output constraints are relaxed, and we write the problem in the following form (considering L_2 norms):

$$J = \frac{1}{2}\min_{\{u,y\}}\sum_{k=0}^{N-1}\left[(1-\alpha_k)\| y_{k+1} - T_{\delta p,k+1}\|_{2,Q}^2 + \alpha_k \| u_k\|_{2,R}^2 + \| v_k\|_2^2 + \| w_k\|_2^2 + \| \varepsilon_k\|_2^2\right]$$

$$\text{such that}\begin{cases} 0 \le u_k \le P_{\max} \\ y_{\min} - w_k \le y_k \le y_{\max,k} + v_k \\ \Delta y_{\min,k} - \varepsilon_k \le y_{k+1} - y_k \\ 0 \le w_k \\ 0 \le v_k \\ 0 \le \varepsilon_k \end{cases} \tag{0.7}$$

Using the state space representation of the system, we express the impulse response of the model and then formulate the problem as a QP optimization problem using a "soft regulation" for the output constraints with 3N or 4N variables [28] and 6N or 7N constraints (whether we consider or not the temperature rate change as a constraint):

$$\begin{array}{c} J = \min_X \frac{1}{2} X' H X + g' X \\ \text{such that } FX \ge h \end{array} \text{ with } \begin{cases} X = [U, V, W, \mathrm{E}]' \\ V = [v_1 \dots v_N]' \\ W = [w_1 \dots w_N]' \\ E = [\varepsilon_1 \dots \varepsilon_N]' \end{cases} \tag{0.8}$$

Penalty parameter

The matrix H is composed of two terms: $H = F_{sf}R + G'QG$. G is composed of the impulse response over the time horizon for prediction H_o; R is the penalty matrix for the minimization of the power while Q is the penalty function for the difference between the room temperature and the set point and F_{sf} is a diagonal matrix used as a scaling factor. At this stage, if we only consider Euclidean norm without additional penalty cost, we have $R = Q = I_{N,N}$ but since $\| G'QG\|_2 << \| R\|_2$, we need to add a scaling factor in order to have two comparable terms. Let sf be the norm of the second term: $sf = \| G'G\|_2^2$, we define F_{sf} as $F_{sf} = sfI_{N,N}$ resulting in two terms for H with comparable norm.

Secondly, we need to include the price signal into the problem: for the strategies *S1* and *S2*, the price signal is interpreted as an on/off switch of the devices, eventually with a change in the set point. For the MPC, the strategy is more sophisticated as the controller has the ability to interpret the price signal. Then, by noting P_{t_k,t_k+H_0} the vector price for the period $[t_k, t_k + H_0]$, we set $R = \mathrm{diag}(P_{t_k,t_k+H_0})$.

As a result, the relative weight between the two objective functions at the sampling time t_k is the maximum price over the horizon of prediction. We might want to adjust this relative weight and, to do so, we need to add an extra weighting parameter α_k in order to maintain the relation between peak and off peak prices. Finally, we set: $R = \mathrm{diag}(\alpha_k)\mathrm{diag}(P_{t_k,t_k+H_0})$ and $Q = I_{N,N} - \mathrm{diag}(\alpha_k)$ with $0 \le \alpha_k \le 1$ a parameter defining the trade-off chosen between "comfort and consumption". In the next sections, we consider that outside the peak period, the objective is only to satisfy the household comfort requirements, thus we set $\alpha_k = 0$ for all t_k in off-peak period and we note α the constant value of the parameter for peak hours. Since our focus is on comfort, we set α =0.1 in the rest of the paper. Increasing α will down low the preheating phase of the controller, resulting in a lower energy consumption at comfort cost.

MPC strategy S3

The first MPC strategy consists in sending a price signal during peak periods. The relation between the peak and off-peak price should be carefully set in order to send the right signal to the regulator but this question is beyond the scope of this study. A wide range of prices can be observed from past experiments. We suggest to set up a 1 to 10 relation between the prices.
In this strategy, we only bound the temperature in a quite large “comfort zone”: 18-23°C.

MPC strategy S4

This strategy is exactly the same as S3 but we add an extra comfort constraint during the control period: $\frac{dT}{dt} \geq -1°\mathrm{C}\cdot\mathrm{h}^{-1}$ if $\frac{dT}{dt} \leq 0$.

Indicators to evaluate and compare load control strategies’ performances

In order to evaluate the full potential of our control strategies, we need to choose adequate performance indicators. Building a global index to evaluate the strategies in terms of power or energy curtailed and in terms of thermal comfort impact is not feasible obviously, then we suggest to use several indicators and to compare strategies based on a grid of performance indicators. Load curtailments and load shiftings can be evaluated by comparing the results under control with the results without control, meaning that we are able to estimate what would have happened without control. In this paper, we only deal with simulations so that we can easily build the reference case. In the next sections, the reference case refers to the situation where no external control is applied. As we suggest two means for control: control through the heating system regulator and control using a MPC, we consider two reference cases: *REF1* and *REF2*. In *REF1*, the heating system is regulated by the regulator embedded in the heating device, as *REF2* the heating system is directly regulated by the MPC. We assume the embedded controller is a PI type, and we set the PI parameters using the Zieger-Nichols closed loop technique. Households choose the thermostat set points (see figure 1). An experiment refers to a simulation with a control strategy applied, a case is a house for which we conducted several experiments under the same external conditions.

The power is the mean of the consumed energy during an elementary interval Δt, and the power curtailed in an experiment is defined as the difference between the power consumed the reference case and the power in the experiment. We also define the control period as the period when a control strategy is applied. If we consider pre-heating strategies before the curtailments, the control period is extended to include the pre-heating phase. The same remark applies in case of post-control strategies. Based on the work of Da Silva [8] some meaningful indicators to assess performances’ strategies are:

1. *Energy savings during control* (referred as *ESDC*, in $\mathrm{kWh}\cdot\mathrm{m}^{-2}$ per day): Difference between the consumed energy with the control strategy and the reference case during the period when the control is applied normalized by the size of the house.

2. *Overconsumption* (referred as *OC*, in $\mathrm{kWh}\cdot\mathrm{m}^{-2}$ per day): Difference between the consumed energy with the control strategy and the reference case during the periods before curtailment (in case a pre-heating phase exists) and right after the curtailment (including any *post control strategy*).

3. *Recovery* (*R*), in %: relation between the *OC* and the ESDC. The recovery index represents the ratio of energy shifted while 1-*R* is the curtailed part index.

4. *Degree-hours of discomfort* (referred as *DH*, in $°\mathrm{C}\cdot\mathrm{h}$ per day) which is the time spent below a certain comfort temperature limit $T_{\mathrm{comfort,lim}}$: $\mathrm{DH} = \int_0^{24\mathrm{h}} \max\left(T_{\mathrm{comfort,lim}}(t) - T(t), 0\right) dt$. In this paper, we choose $T_{\mathrm{comfort,lim}}(t) = T_{\mathrm{sp}}(t) - 1°\mathrm{C}$ (1°C tolerance below the set point).

One could note that time spent above an upper comfort limit is also important, especially in summer conditions, but as we evaluate load curtailment strategies in winter conditions and for simplification purpose we neglect this situation.

Where the strategies are applied for several days, we consider the mean values for the indicators. In addition to those indicators, and based on the previous observations, we suggest that discomfort conditions could appear not only when the room temperature falls below the $T_{\mathrm{comfort,lim}}$ limit, but also if the room temperature drops too fast during the control phase. People are more likely to notice rapid changes in temperature than to noticie that the temperature is different from their "comfort temperature". This situation is very likely to occur in low insulation buildings, which account for a large part of the building stock heated with electrical convectors in France. Because of their poor insulation, the nominal power for the systems used in these buildings is largely above the required power in low consumption buildings, therefore their energy consumption is far beyond the one in more recent buildings. As a consequence, they represent a very interesting potential for load control action aiming at actions such as peak shifting or load curtailments. We add an extra indicator, *STDH*, representing the variations of the temperature in the building. In this simulation, this indicator is closely linked to the building time constant but for an *in situ* situation, *phenomena* such as internal gains,… could have a significant impact on it. This indicator represents the mean temperature drop during a control period in $°\mathrm{C}\cdot\mathrm{h}$ per day:

$$\mathrm{STDH} = \frac{1}{T_{\mathrm{control}}} \int_{T_{\mathrm{control}}} \min\left(\frac{dT(t)}{dt}, 0\right) dt \tag{0.9}$$

Results

In the results presented below, we used a curtailment period of 2 hours, from 6pm to 8pm, and occurs every working day. The prediction horizon for the MPC is set to 6 hours with a 5 minutes time step for prediction and the predictor loop is set to 15 minutes (the optimal trajectory is recalculated every 15 minutes). This choice represents a trade-off between accuracy and calculation speed [18]. We conducted the simulation during the whole winter period but for clarity, we only present here the results for a typical day, and we compute mean values for the indexes.

Evaluation of the experiments for a single case

We present here the results for one specific case: we consider a house built under the first generation of French thermal regulations (1988), with internal insulation layer (lower insulation) for a cold winter day. We used the scenario 1 for this simulation.

The two reference cases (*REF1* and *REF2*, in solid purple line in figures 2 and 3) give similar results but there is a slight overtaking in the case the regulator is a PI. This can be improved by tuning more precisely the anti-windup loop.

For this low insulated building, the strategy *S1* (figure 2) is not suitable as the building thermal inertia is not enough important and the temperature drops very quickly. The strategy *S2* is better as the final room temperature is above the one reached with *S1* but the preheating phase leads to an even bigger temperature variation in a small period, meaning that the households might face a discomfort situation resulting from this temperature variation.

The MPC strategy *S3* (figure 3) results in a similar conclusion as for the strategy *S2*, even though this strategy allows a final temperature at around 18°C (lower constraint bound), the temperature amplitude variation in the period {pre-heating + control phase} is excessive. Moreover, as the temperatures during this period are above the ones found with S2, the discomfort might be even more noticeable. One can notice that is this particular case, it was cheaper to unfulfill the upper comfort constraint during the pre-control phase. Adjusting the parameter α to a bigger value limits the amplitude of the temperature rise but the comfort is not improved.

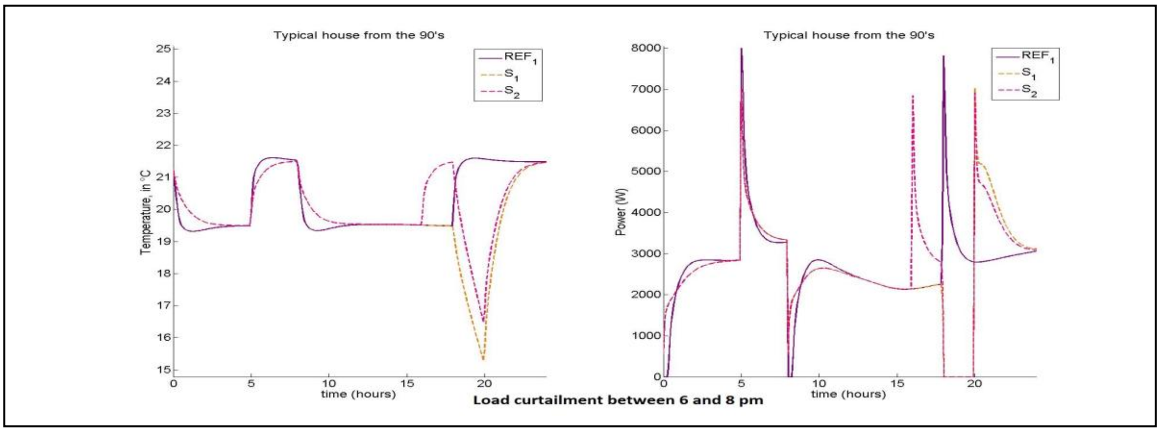

Figure 2: Evolution of the room air temperature and load curve for S1 and S2

Finally, the strategy *S4* (figure 3) is of great interest for this type of buildings: the temperature is slightly raised prior to the control period but with an amplitude similar to the magnitude for set point changes. Then the system is intermittently turned off and on during the control period in order to correct the temperature drop rate and respect the constraint but the consumed power is noticeably lower as compared to the periods without control. As a result, the power shifted and / or curtailed is less important than with any of the other strategies but this system is more likely to complete households thermal comfort expectations.

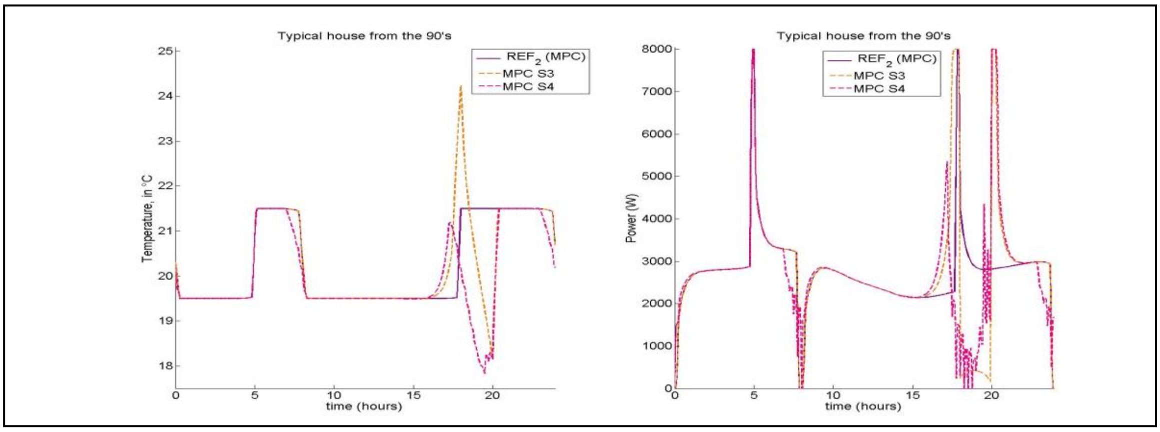

Figure 3: Evolution of the room air temperature and load curve for S3 and S4

In the next section, we analyze those results according to the indicators presented above for the same case study. The results are presented in figure 4 where each strategy is represented with a colored dot. (There are 3 dots of each color, each one representing a scenario).

As it can been seen in left graph of figure 4, any strategy leads to a curtailed load as the overconsumption is always below the energy savings. For the strategies 1 to 3, the STDH is kept constant and the DH indicator is made smaller when the scenario reference is changed. With the strategy *S4*, the DH indicator is smaller than in *S3* thanks to the additional output constraint and in addition STDH is made smaller when the scenario changes meaning than this control is more flexible than the other ones.

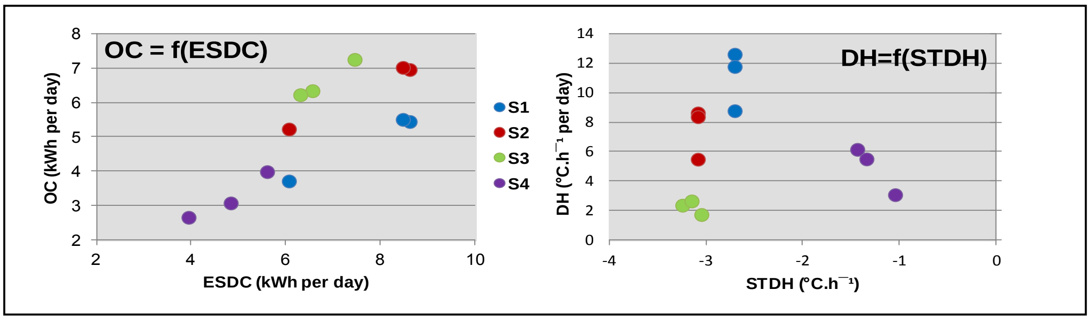

Figure 4: Comparison of the experiments for a typical house from the 90's

In the next section, we compare those strategies for the different cases in order to evaluate the resulting load flexibility that might arise.

Evaluation of the strategies among the cases

We now consider the 6 cases studied (3 levels of external or internal insulation) and we assume that we are in the most adverse scenario: the temperature set point is switched at 6pm in the evening to the comfort value. The results are summarized in the figure 5. The same colors are used to distinguish the strategies and in addition, each type of house is represented by a bullet shape.

Table 2: Recovery index (%) for 3 study cases

Building type / Strategy	***S1***	***S2***	***S3***	***S4***
Low level of insulation (internal)	63.2%	80,7%	96,6%	63,6%
Medium level of insulation (internal)	86%	99.4%	100,4%	95,2%
High level of insulation	98.5%	106%	100%	100%

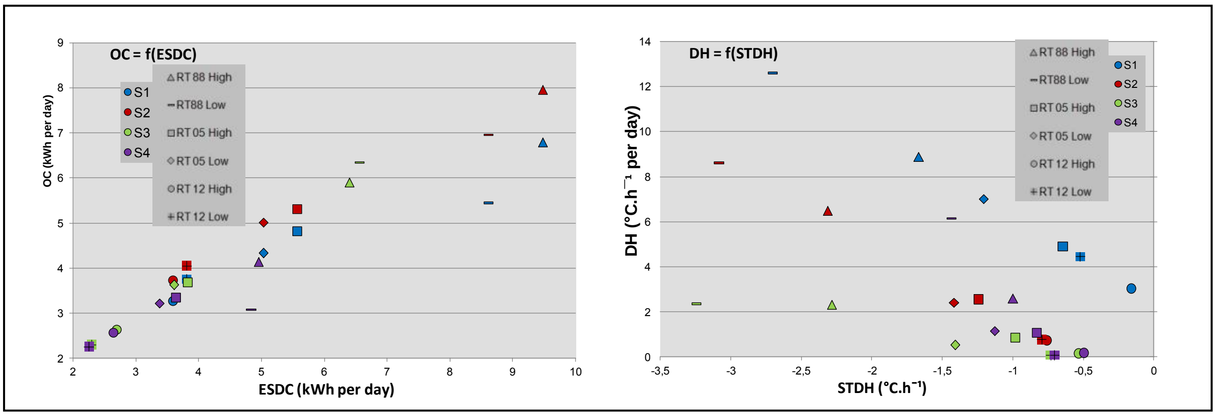

Figure 5: Index results for the 6 cases

On the left side of figure 5 are the energy indicators while the comfort ones are presented in the right side. The results from strategies *S1* and *S2* cover a larger range of values while strategies *S4* (and *S3* to some extent) are more homogeneous meaning that those strategies tend to smooth the buildings behavior. For the most recent types of houses (referred as *RT12*), the results are very similar among the strategies, which was expected: as the level of insulation is high, the thermal inertia of the house is sufficient to handle simple strategies such as *S1* and even *S2* without creating a discomfort situation because the temperature falls slowly during the control period. As a result, implementing complex strategies in those type of buildings is not pertinent. For low insulation buildings, the strategy *S4* limits the rate of temperature fall and thus improves the *DH* value, making those buildings similar to high insulation ones in terms of comfort performance during control period.

The recovery factors for the 4 strategies and with 3 levels of building insulation are in table 2. The recovery index mainly depends on the insulation level but strategies such as S1 and *S4* are more satisfactory because as the recovery index remains below 100%, those strategies allow load curtailments and not only load shiftings. *S2* and *S3* give higher *R* values as compared to the other ones. This is due to the fact that in those strategies, the pre-heating phase results in a important overconsumption prior to the curtailment period but the thermal state at the end of the control period is not so different from the one in the case of *S1* and *S4.*

Table 3: Typical Summary of the results

Building type	Insulation	Best strategy to preserve comfort during a load control event	Curtailment possible?	Exceeds reference consumption?
Low insulation	Internal	S4	Yes	No
	External	S4	Yes	No
Medium insulation	Internal	S4 (S1)	No (yes)	Limit (no)
	External	S1 (S4)	yes (limit)	No (no)
High insulation	Internal	S1	No	Limit
	External	S1	No	No

We summarized the best identified strategies for each case in table 3. The “best” choice has been set according to the double lecture energy/comfort performance. Whenever the strategies give very similar results, we favor the simplest solution. In case more than one strategy is relevant we left the two strategies, the one to favor is the first written, while the second is in brackets (the commentary into brackets concerns the second strategy). For instance, for the type “medium external insulation” we choose *S1* as its energy performance is more satisfactory and the overtaking in comfort restrictions remains in an acceptable range while *S4* decreases the potential for curtailments (bigger *R* value). Similarly, for “medium internal insulation”, *S4* is to favor as *S1* may result in an unsatisfactory comfort situation. Whenever the *R* index is close to 100 (over 95%), we considered that we are in a limit of overconsumption case.

Concluding remarks

In this study, we have proposed too strategies for load control based on a MPC controller and adapted to preserve comfort during a peak period. We compared these strategies with simple strategies requiring few means to be implemented: cutting the power during a peak period (S1) and cutting it with a pre-heating phase (S2). We compared the performances of those strategies to provide load flexibility for difference building cases. Strategy *S2* is never satisfactory, since for low insulation buildings it leads to a high temperature amplitude variation, and for highly insulated buildings, it results only on shifting flexibilities while low consumption buildings are expected to provide more flexibility as comfort is less an issue. Therefore the strategy *S1* gives very good results on those buildings. For low insulated buildings, the low mass envelope provides a good source for load shifting but as comfort is degraded too much, the strategy consisting in limiting the temperature variation gave the most satisfactory results: an *R* index close to the one with *S1* but with comfort indexes substantially increased. Finally, for intermediary insulated buildings, additional work on the type of insulation and building characteristics is necessary in order to refine the results.

In future work, we will refine the parameterization of the MPC model (weighting parameters) and assess its performance under degraded weather conditions considering disturbances on the forecasted external data.

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